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FLIGHT VERIFICATION OF THE ADVANCED FLIGHT CONTROL ACTUATION SYSTEM (AFCAS) IN THE T-2C AIRCRAFT

Rockwell International

Columbus Aircraft Division
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JUNE 1978

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The feasibility of the Advanced Flight Control Actuation System (AFCAS) concept was demonstrated in a T-2C aircraft. The test installation contained a localized 8000 psi (55 MPa) hydraulic power supply, control-by-wire direct-drive modular design rudder actuator, electronic drive unit, and force transducer. The system performed exceptionally well during 10.2 hours of flight evaluation. Successful completion of this project confirmed prior analyses and laboratory testing.

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EXECUTIVE SUMMARY

1.0 PURPOSE OF THE PROGRAM

The complexity of aircraft flight control systems has increased year-by-year until present initial costs and required maintenance time are approaching prohibitive levels. This situation is due primarily to the design philosophy that improvements and refinements are best achieved by adding on accessories and/or components to proven, traditional systems. Broad new approaches and technologies involving advances in power generation, transmission, control, and actuation will be required to alleviate complexity in future Navy aircraft. The Advanced Flight Control Actuation System is a significant step in this direction.

2.0 BENEFITS TO THE NAVY

The Advanced Flight Control Actuation System (AFCAS) program introduces concepts for direct computer control of primary surface actuators. Computer processed signals are applied directly to primary actuators, eliminating traditional augmentation and secondary actuators with contaminant sensitive electrohydraulic servo valves. The actuator design employs a "building block" approach which standardizes various elements in the assembly. This modularization provides simplicity, hardware commonality, and permits the development of actuator classes. Combat survivability is improved through the use of localized hydraulic power supplies.

Adoption of AFCAS concepts will permit significant gains in several areas:

- Reduction in MMH/FH from 1.0 to 0.2
- Reduction in ground crew training
- Improved reliability and increased utilization
- Lower life cycle costs
- Improved vulnerability characteristics
- Simplified redundancy requirements

3.0 INVESTIGATION PROCEDURE AND RESULTS

3.1 Background Information

The AFCAS program examined the feasibility of three separate concepts:

Control-By-Wire:	Computer processed signals are applied to force motor direct-driven flow control valves mounted on hydraulic actuators operating at 8000 psi (55 MPa).
Modular Actuator:	Actuators are designed with commonality features which permit the formation of "actuator classes" and the fabrication of single, parallel, or tandem actuators using modular "building blocks".
Localized Power:	Independent pump/reservoir hydraulic power packages provide 8000 psi fluid to actuators in specific, localized areas in the aircraft.

The program consisted of five phases. Phase I was a feasibility study which established that a direct-drive flow control valve, modular configured actuator, and localized power package could be readily integrated into a computer-operated, control-by-wire system. Efforts to confirm the practicality of AFCAS concepts were begun in Phase II with the design and fabrication of an engineering model control-by-wire, modular hydraulic servo actuator. Phase III involved conducting laboratory performance tests on the actuator. Major achievements accomplished in Phase III were:

- Successful operation of a direct electrical control muscle actuator for primary flight control surfaces.
- Use of building-block elements to assemble dual tandem, dual parallel, and single actuator configurations.
- Successful operation of a control-by-wire hydraulic actuator utilizing 8000 psi (55 MPa) operating pressure.
- Successful performance of a laboratory-type electronic drive unit which provided high immunity to circuitry failures.

An 8000 psi control-by-wire modular rudder actuator was designed and fabricated in Phase IV. The actuator was built for flight testing on a T-2C twin engine turbojet trainer. Phase V, reported herein, demonstrated the feasibility of AFCAS concepts by flight testing.

3.2 Flight Verification of AFCAS

3.2.1 Test Installation - The directional control system in a T-2C airplane was changed to a full-powered control-by-wire test installation containing:

- Hydraulic rudder actuator
- Electronic drive unit
- Localized hydraulic power unit
- Force transducer

The existing hydraulic system was altered to operate at two pressure levels: 3000 psi (21 MPa) and 8000 psi (55 MPa). Engine driven pumps powered the 3000 psi system in the usual manner. A localized motor/pump unit was added to power the rudder actuator. The modified system functioned like the original T-2C directional system except the rudder was hydraulically powered instead of manually operated.

The T-2C cable system between the rudder pedals and rudder was changed to incorporate the control-by-wire test installation. The rudder pedal cables were attached to a sector which operated a force transducer. Force on the pedals was converted to a proportional electric voltage from the transducer. This command signal was conditioned by an electronic drive unit which powered a torque motor on the rudder actuator. The torque motor in turn operated a single stage flow control valve on the actuator.

3.2.2 Preflight Tests - A laboratory setup integrating components to be installed on the T-2C was assembled and performance tested. Six 1-1/2 hour simulated flights were conducted on the laboratory setup to verify reliability. Following system installation on the aircraft, hangar tests were conducted using comprehensive checkout procedures. A ground demonstration test was conducted on the T-2C to simulate a one hour flight from take-off to landing, and provide a means to final check system operation and instrumentation.

3.2.3 Flight Tests - The primary objective was to verify the feasibility of AFCAS concepts by flight testing a control-by-wire, direct drive actuation system powered by a localized motor/pump unit. The flight plan was designed to determine directional control characteristics at several altitudes up to 30,000 feet (9.1 km) and various speeds up to 340 knots (174 m/s). The first two flights were dedicated to confirming satisfactory operation. Subsequent flights were scheduled to evaluate system performance while accumulating 10 flight hours. Two pilots participated in the program.

Both test pilots stated that performance of the AFCAS installation was completely satisfactory. Comments made by the pilots concerning their flights were:

- The AFCAS installation worked exactly as designed
- No malfunctions occurred
- System pressure was steady
- Hydraulic fluid temperatures were normal
- Directional control response was judged to be superior to the production T-2C
- Pilot adaptation to "force control" of the rudder was quickly and easily acquired. Reaction of the aircraft provided the clues to close the loop.

4.0 DIGITAL CONTROL OF AFCAS

The AFCAS concept is intended for application to automatic, computer operated flight control systems. The AFCAS flights did not demonstrate the full performance capabilities of the test hardware since the T-2C did not have computer operated controls. Company funded investigations at the Columbus Aircraft Division have verified the feasibility of controlling AFCAS actuators directly by a digital computer.

A laboratory setup was assembled which interfaced AFCAS direct-drive actuation circuits with a programmable digital processor. The processor was used for closed loop control of a direct-drive dual tandem actuator built early in the AFCAS program. The computer was programmed to generate the error signal in four formats: (1) dc analog, (2) pulse-width modulation, (3) bang-bang, and (4) time dwell modulation. Frequency response was determined for all four modes. Simulated failure tests confirmed that digital control signals are compatible with the automatic failure-compensation features inherent in the AFCAS electronic drive unit.

5.0 CONCLUSIONS

The feasibility of the AFCAS concept was demonstrated in a T-2C aircraft. The AFCAS installation functioned exceptionally well. Successful completion of this program confirmed the results of prior analyses and laboratory investigations. The ease with which flight testing was accomplished verified that direct-drive, control-by-wire 8000 psi actuation systems can be designed, fabricated, and maintained without special techniques or state-of-the-art advances.

6.0 RECOMMENDATIONS

The test installation was an analog control-by-wire system; the AFCAS concept is intended for application to digital control-by-wire systems. The Columbus Aircraft Division has confirmed by laboratory testing that AFCAS components are compatible with digital control-by-wire components. Therefore, it is recommended that the AFCAS test system currently installed on the T-2C be modified by the addition of a micro-processor and that additional flight testing be conducted. This will provide the Navy with an economical approach to demonstrate, in flight, advantages of the direct-drive features of AFCAS with computer control.

A second recommendation is concerned with the direct-drive control module (force motor and spool/sleeve valve). The motors and valves procured for AFCAS projects were designed for concept verification only, and were not intended to be production configurations. LHS and AFCAS technology have progressed sufficiently that effort should now be directed toward optimized designs which can be integrated into future production applications.

PREFACE

This report documents research conducted by the Columbus Aircraft Division of Rockwell International Corporation, Columbus, Ohio, under Contract N62269-76-C-0201, with the Naval Air Development Center, Warminster, Pennsylvania. Technical direction was administered by Mr. T. Jansen, Program Engineer, Aero-Mechanical Branch, Aircraft and Crew Systems, Naval Air Development Center (Code 6013), and Mr. J. Schonowski, Flight Controls Systems Unit, Mechanical Equipment Branch, Naval Air Systems Command (AIR-530311C).

This report discusses flight testing of a control-by-wire, direct-drive, 8000 psi (55 MPa) actuation system in the yaw axis of a T-2C aircraft. This work was related to tasks performed under Contracts N62269-72-C-0108, N62269-73-C-0405, and N62269-75-C-0311.

Acknowledgement is given to the following for their participation on this project:

Mr. D. Cahill	Design Engineer
Mr. L. Grieszmer	Design Engineer
Mr. B. Holland	Systems Engineer
Mr. B. Mathena	Electronics Engineer
Mr. D. Bomba	Chief, Flight Test Projects
Mr. R. Dixon	Manager, Test Vehicle Maintenance
Mr. R. Cockburn	Test Pilot
Mr. R. Wenzell	Director, Flight Operations and Logistics (and Test Pilot)
LCdr. T. Giardina	Navy Flight Representative

Appreciation is extended to the many individuals who provided helpful support and constructive criticism of the program; in particular, Mr. T. Jansen of the Naval Air Development Center, Mr. J. Schonowski of the Naval Air Systems Command, and Mr. I. Dudley of the Columbus Aircraft Division of Rockwell International Corporation.

Discussions in this report of components supplied by various manufacturers shall not be construed as either an endorsement or criticism of any component. The government incurs no liability or obligation to any supplier from the information presented herein.

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1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

The development of Advanced Flight Control Actuation Systems (AFCAS) for next generation aircraft has been a joint undertaking by the Navy and Rockwell International Corporation since 1972. This report presents the results of flight testing a subsystem to verify concepts, laboratory evaluations, and component designs developed in prior phases of the AFCAS program.

The complexity of flight control systems has increased year-by-year until present initial costs and required maintenance time are approaching prohibitive levels. This situation is due primarily to the design philosophy that improvements and refinements are best achieved by adding on accessories and/or components to proven, traditional systems. Broad new approaches and technologies involving advances in power generation, transmission, control, and actuation will be required to alleviate complexity in future Navy aircraft. The Advanced Flight Control Actuation System is a significant step in this direction.

Phase I of the AFCAS program was a study which examined the feasibility of three separate concepts:

Control-By-Wire:	Computer processed signals are applied to force motor direct-driven flow control valves mounted on hydraulic actuators operating at 8000 psi (55 MPa).*
Building-Block Actuator:	Actuators are designed with commonality features which permit the formation of "actuator classes" and the fabrication of single, parallel, or tandem actuators using modular "building blocks".
Localized Power:	Independent pump/reservoir hydraulic power packages provide 8000 psi (55 MPa) fluid to actuators in specific, localized areas on the aircraft.

*The metric equivalent of 8000 psi is 55,158,000 pascals or 55 megapascals (55 MPa). This newly adopted method of defining pressure is based on the International System of Units (SI) and has been approved by DOD, reference ASTM E 380-76, Standard for Metric Practice, dated 19 January 1976. All dimensions in this report have metric equivalents given in parentheses except where unnecessary repetition would occur or when a general note is used on illustrations. A summary of metric conversions is given on page 106.

Phase I established that a direct-drive flow control valve, modular configured actuator, and localized power package could be readily integrated into a computer-operated, control-by-wire system. Adoption of AFCAS concepts should enhance flight control system maintainability, reliability, combat survivability, and lower initial costs, Reference 1.

Efforts to confirm the practicality of Phase I concepts were begun in Phase II with the design and fabrication of an engineering model, 8000 psi (55 MPa), control-by-wire, modular configured aircraft type hydraulic servo actuator, Reference 2. Electrical inputs were applied to force (torque) motors employing cobalt samarium permanent magnets. Motor output was connected directly to single stage spool/sleeve type flow control valves. The force motors and flow control valves could be integrated into dual tandem, dual parallel, or single actuator configurations.

Phase III involved conducting laboratory performance tests on the engineering model actuator(s) built in Phase II, Reference 3. Static and dynamic tests were conducted on the force motors, motor/valve subassemblies, electronic drive unit, and actuator assemblies including dual system tandem, dual system parallel, and single system configurations. The dual tandem actuator was tested under load. Major achievements accomplished in Phase III were:

- Successful operation of a direct electrical control "muscle" actuator for primary flight control surfaces.
- Use of building-block elements to assemble dual tandem, dual parallel, and single actuator configurations.
- Successful operation of a control-by-wire hydraulic actuator utilizing 8000 psi operating pressure.
- Successful performance of a laboratory type electronic drive unit which provided high immunity to circuitry failures.

In Phase IV, an 8000 psi (55 MPa) control-by-wire, modular rudder actuator was designed and fabricated for future flight testing on a T-2C airplane, Reference 4. Actuator design criteria were based on T-2C aerodynamic considerations, envelope constraints, and single system hydraulics. Actuator output was commanded by a single stage spool/sleeve valve driven directly by a permanent magnet force motor. The force motor was to be powered by an electronic drive unit which received inputs from a force transducer in the rudder system and position transducers on the actuator. A localized hydraulic power unit was planned to supply 8000 psi (55 MPa) pressure for the rudder actuator.

1.2 OBJECTIVE

The objective of Phase V was to design, fabricate, and test a subsystem to verify the feasibility of the Advanced Flight Control Actuation System - Building Block concept. The test system was to be installed in a T-2C twin engine turbojet trainer.

1.3 TECHNICAL APPROACH

The directional control system in a T-2C airplane was changed to a full-powered control-by-wire test installation containing:

- Hydraulic rudder actuator
- Electronic drive unit
- Localized hydraulic power unit
- Force transducer

The existing hydraulic system was altered to operate at two pressure levels: 3000 psi (21 MPa) and 8000 psi (55 MPa). Engine driven pumps powered the 3000 psi system in the usual manner. A localized motor/pump unit was added to power the rudder system which was formerly operated manually by the pilot. The original 3000 psi and newly added 8000 psi systems shared the existing reservoir and return lines. The T-2C electrical system was altered to power the localized motor/pump unit and electronic drive unit. The modified system functioned the same as the basic T-2C system except the rudder was hydraulically powered instead of manually operated.

The original cable system between the rudder pedals and rudder was changed to incorporate the control-by-wire test installation. The rudder pedal cables were attached to a sector which was prevented from rotating by a force transducer. Force on the pedals was converted to a proportional electric voltage from the transducer. This command signal was conditioned by an electronic drive unit which powered a torque motor on the rudder actuator. The torque motor in turn operated a single stage flow control valve on the actuator.

The direct-drive, 8000 psi rudder actuator designed and fabricated in Phase IV was modified to incorporate a bypass valve. This device allowed the rudder to seek the trail position if system pressure were lost. In the event of a "hard-over" type electronic failure, the pilot could permit the rudder to trail by turning the 8000 psi motor/pump unit "off".

The electronic drive unit was designed, fabricated, and packaged to be a flightworthy assembly. The unit had dual channels with sub-circuits which were dualized. The circuitry was designed with redundancy features which provided high immunity to component failures.

Requirements were established for an 8000 psi localized hydraulic power supply. The pump used was the same unit employed for flight testing in the Lightweight Hydraulic System (LHS) development program, References 5 through 13, except delivery was reduced to match rudder actuator flow rates and to lower input power requirements. The pump was mated to an off-the-shelf, aircraft type 28 volt DC motor.

The force transducer incorporated in the test system was designed specifically for this application. The transducer utilized two linear variable differential transformers mounted in series.

All major components in the test installation were assembled in the laboratory for integration testing. Investigations were made to determine if detrimental pressure oscillations or surges were present. Motor current and system heat rejection were measured. Frequency response tests were conducted on the actuator/system. Nine hours of simulated flight testing were performed to evaluate the endurance capability of system components.

The test system was installed in a bailed T-2C with instrumentation for monitoring pressures, flows, temperatures, etc. Standard parameters such as air speed, altitude, engine RPM, etc., were also instrumented. Flight data were collected by photorecorder and telemetry systems.

Procedures were established for system checkout, ground demonstration, and flight testing. Approximately ten hours of flight time were logged on the test system at various altitudes and airspeeds. Pilot observations and instrumentation data were used as a basis for evaluating the AFCAS installation.

2.0 T-2C AIRPLANE

2.1 GENERAL DESCRIPTION

The T-2C "Buckeye" is built by the Columbus Aircraft Division of Rockwell International Corporation. The Buckeye is a two-place, subsonic trainer powered by twin turbojet engines. The aircraft is designed for both land and carrier based operations. Distinguishing features include wide-track tricycle landing gear, straight tapered wings, and low slung intake ducts, Figure 1.

The T-2C is used as a basic trainer for military pilots, and is equipped for cross-country flight, night flying, and low altitude, high speed navigation exercises. Maximum level flight speed of the Buckeye is 465 knots (239 m/s) at 15,000 feet (4.6 km); the service ceiling is 45,000 feet (13.7 km). Take-off and landing speeds are in the range of 95 to 110 knots (49 to 57 m/s). A typical take-off gross weight is 13,000 pounds (5900 kg).

Dual power sources are provided for the electrical, hydraulic, and air conditioning systems. The flight control system includes hydraulic full-powered ailerons, a boosted elevator, and an electric trim system; rudder operation is manual. The aileron and elevator actuators are part of mechanical linkage connecting the pilot's stick to the control surfaces. Thus, in the event of a hydraulic system malfunction, control of the aircraft can be accomplished manually.

2.2 HYDRAULIC SYSTEM

The T-2C has a 3000 psi (21 MPa), Type II (-65 to +275°F) (-54 to +135°C) single hydraulic system. Two pumps, one on each engine, provide power to operate the landing gear, speed brakes, arresting hook, aileron actuator, and elevator boost package. The pumps are constant pressure, variable delivery, axial piston designs. Each pump is capable of delivering 4.9 gpm (18.5 L/m) at 7800 rpm. Hydraulic fluid (MIL-H-5606) is supplied to the pumps by an air/oil type reservoir pressurized by engine bleed air. Fluid cleanliness is maintained by 5 micron absolute filters.

One pump can adequately handle all flow demands. However, if supply pressure should drop below 1800 psi (12 MPa), a priority valve is used to insure operation of the aileron and elevator actuators. A cockpit controlled shutoff valve is installed in the aileron/elevator subsystem to permit simulating loss of power for training purposes. The landing gear and arresting hook can be lowered and locked by gravity, if desired. The wheel brakes have an independent hydraulic system.

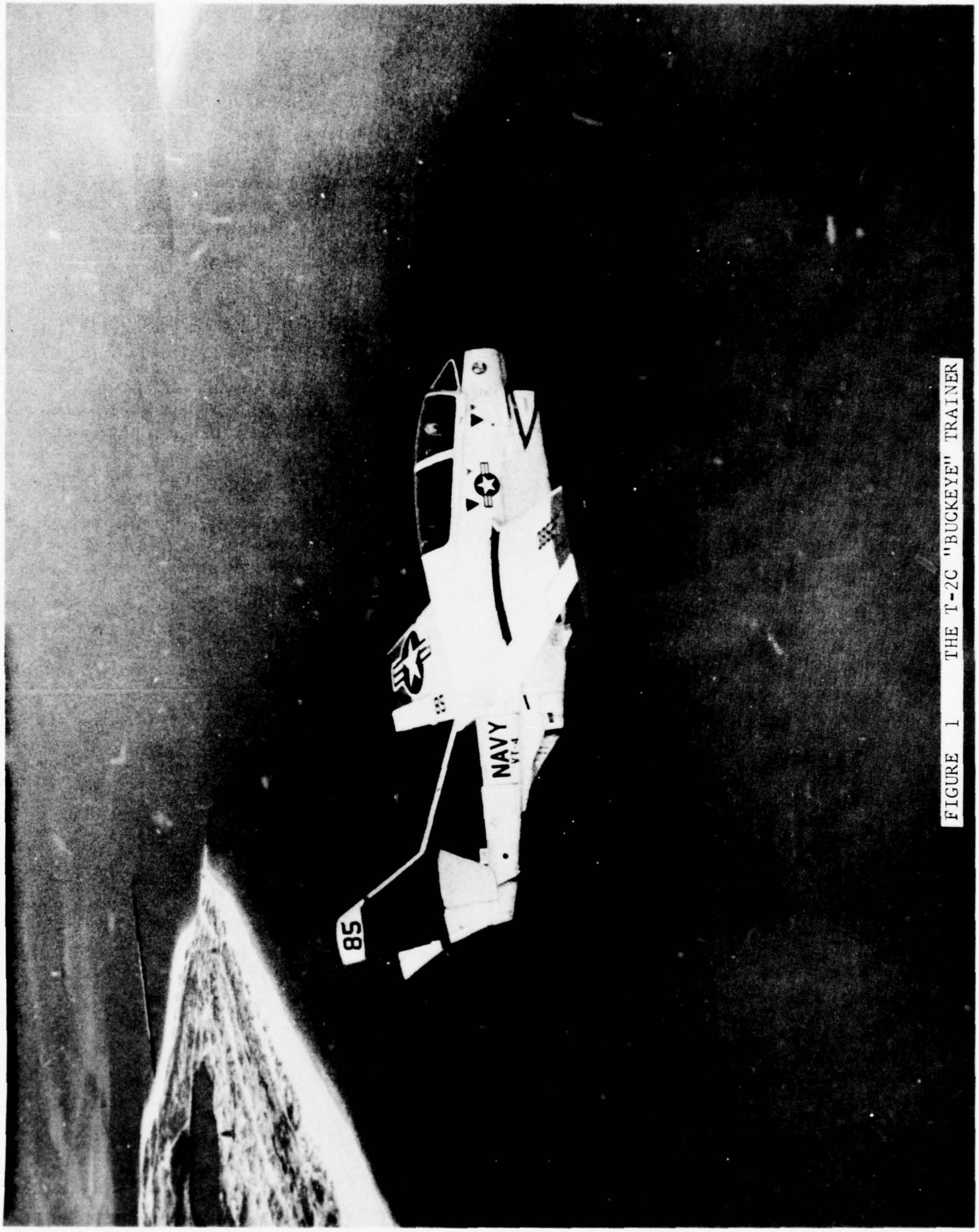


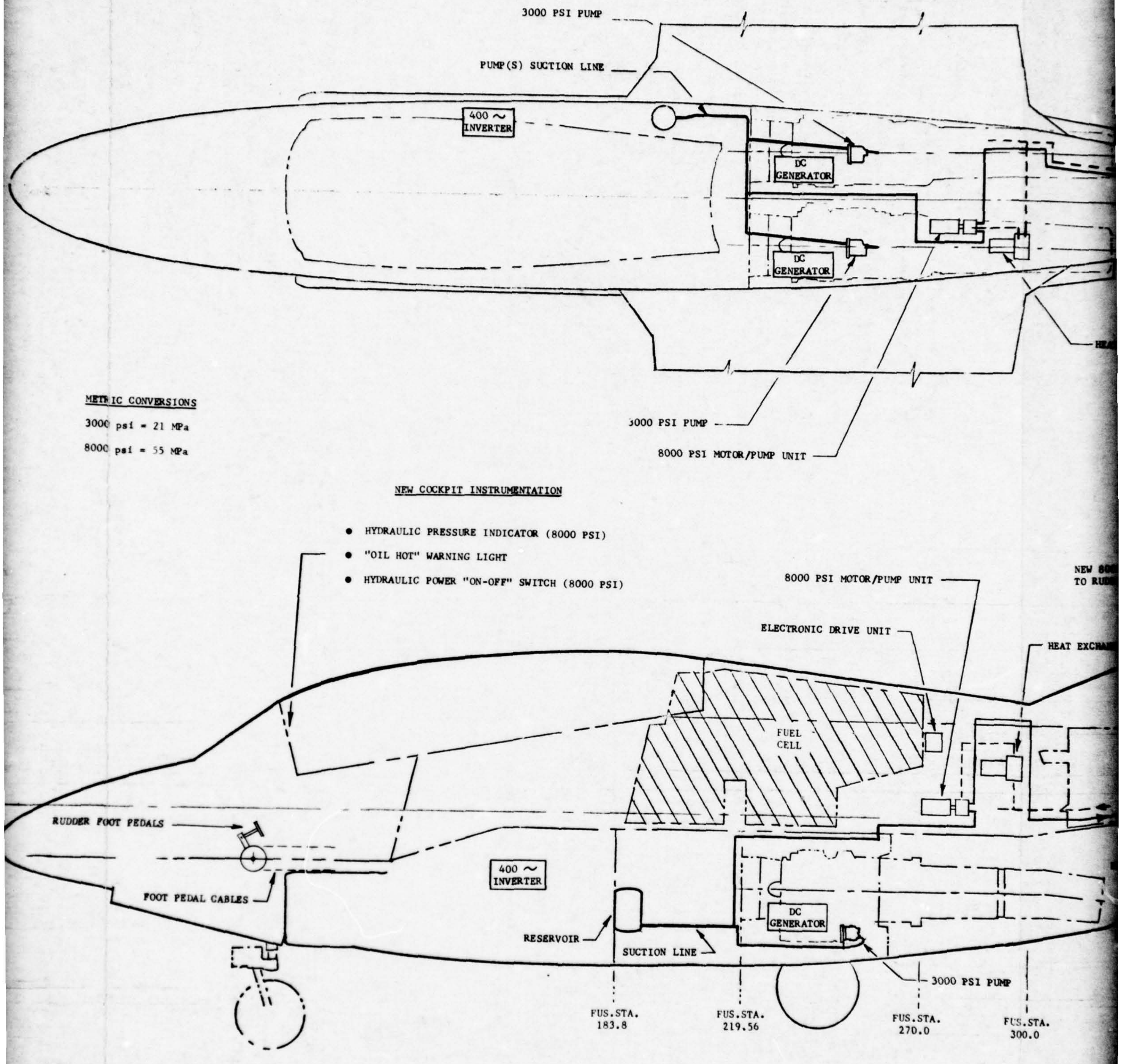
FIGURE 1 THE T-2C "BUCKEYE" TRAINER

2.3 ELECTRICAL SYSTEM

Electrical power is supplied by two 28 volt DC 300 ampere starter-generators, one mounted on each engine. The generators are connected for parallel operation and power the primary bus. Output voltages are regulated for varying loads and engine speeds.

Two nickel-cadmium 24 volt re-chargeable batteries are used for engine starting and emergency DC power. The batteries are normally connected in parallel, but are used in series for engine starting.

A portion of the 28 volt DC power is converted to 115 volt 400 Hz AC power by two rotary inverters. Inverter No. 1 produces 500 volt-amperes for instruments; inverter No. 2 generates 1500 volt-amperes for avionics and serves as a backup source for instrument power.


3000 PSI PUMP
PUMP(S) SUCTION LINE
400 ~ INVERTER
DC GENERATOR
DC GENERATOR
METRIC CONVERSIONS
3000 psi = 21 MPa
8000 psi = 55 MPa
3000 PSI PUMP
8000 PSI MOTOR/PUMP UNIT
NEW COCKPIT INSTRUMENTATION
• HYDRAULIC PRESSURE INDICATOR (8000 PSI)
• "OIL HOT" WARNING LIGHT
• HYDRAULIC POWER "ON-OFF" SWITCH (8000 PSI)
8000 PSI MOTOR/PUMP UNIT
ELECTRONIC DRIVE UNIT
FUEL CELL
RUDDER FOOT PEDALS
400 ~ INVERTER
FOOT PEDAL CABLES
DC GENERATOR
RESERVOIR
SUCTION LINE
3000 PSI PUMP
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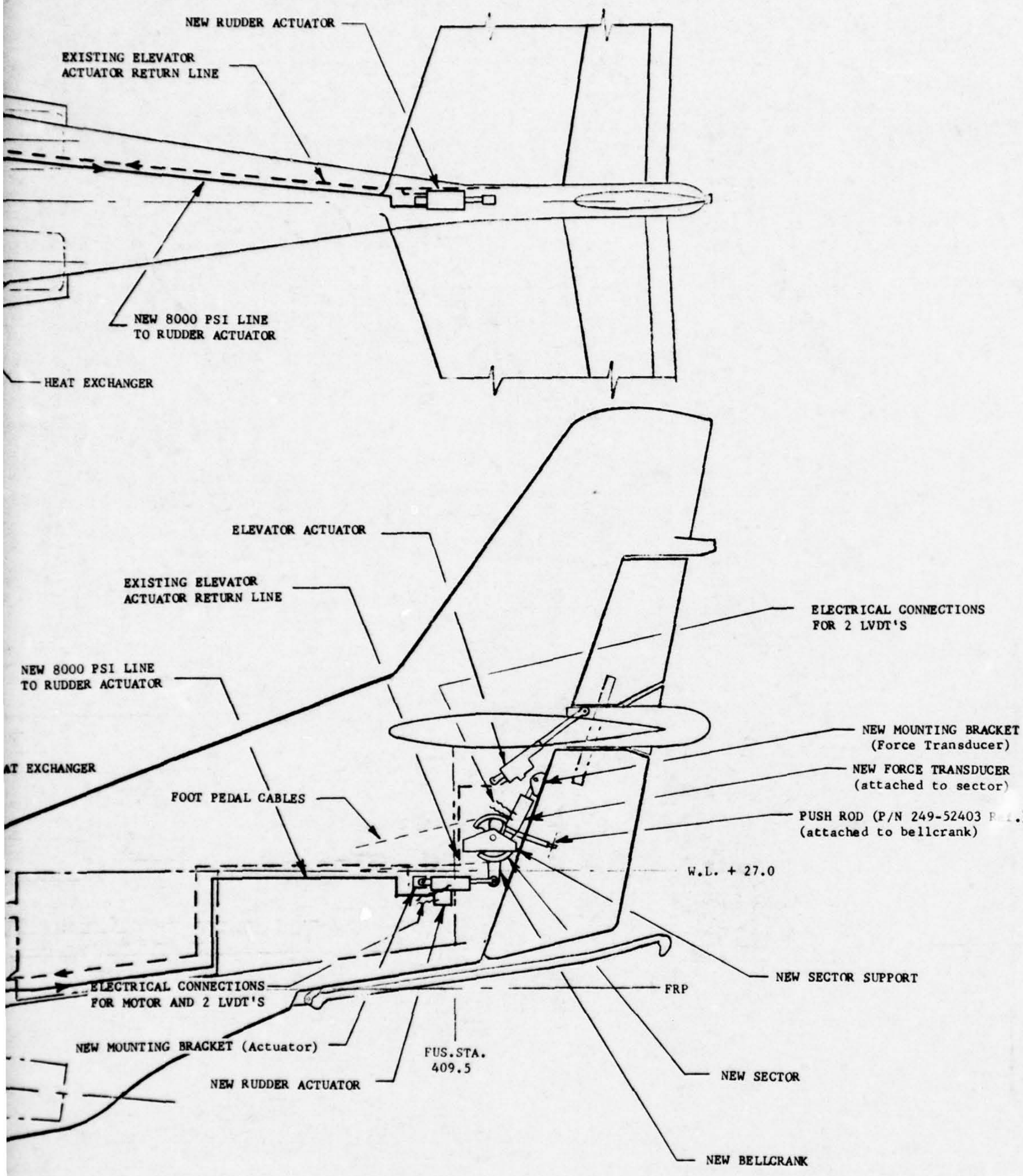


FIGURE 2 AFCAS TEST INSTALLATION

3.0 AFCAS TEST INSTALLATION

3.1 GENERAL DESCRIPTION

The directional (rudder) system in a bailed T-2C (BuNo. 152382) was changed from a manual to a full-powered control-by-wire system for the AFCAS program. Principal components in the test installation were:

- Hydraulic rudder actuator
- Electronic drive unit
- Localized hydraulic power unit
- Force transducer

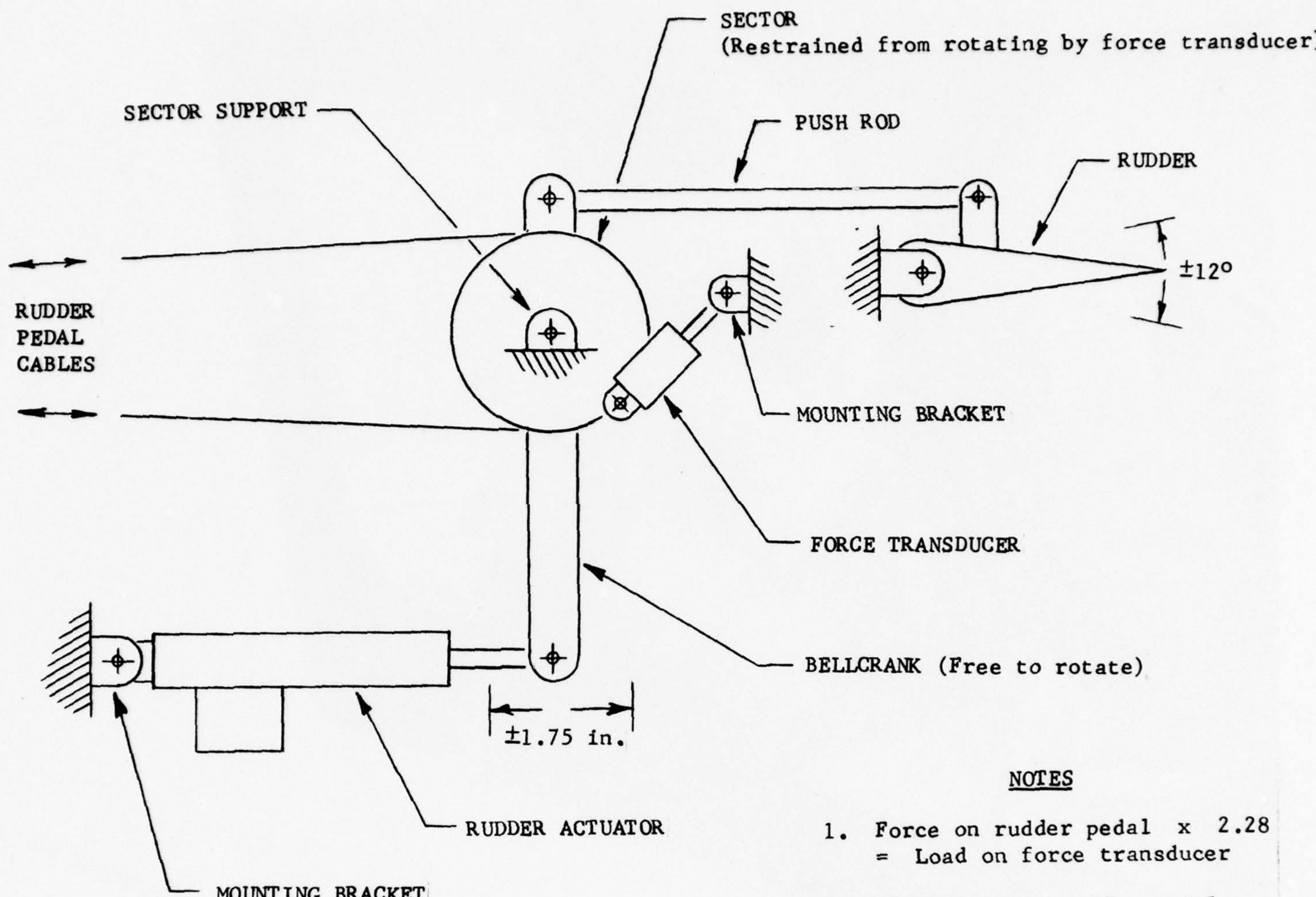
Modifications required in the T-2C to accommodate the new installation are shown on Figure 2. Details of the modifications are discussed in the following sections under four general headings: mechanical system, hydraulic system, electrical system, and instrumentation.

3.2 MECHANICAL SYSTEM

Elements of the mechanical system are listed below and depicted schematically on Figure 3. The installation is shown pictorially on Figure 4; details are given on Figure 5.

Part No.	Description
8691-524001-011	Sector assembly
8691-524001-013	Sector support
8691-524001-021	Bellcrank assembly
8691-524001-041	Rudder actuator mounting bracket
8691-524001-053	Force transducer mounting bracket

The T-2C rudder has a travel of $\pm 25°$. For safety reasons, rudder travel was reduced to $\pm 12°$ in the test installation by limiting actuator stroke. This permits the pilot to land safely with a "hard-over" rudder, opposite engine out, and three knot cross-wind.



<u>NOTES</u>

1. Force on rudder pedal x 2.28
   = Load on force transducer

2. 90 lb load on rudder pedal
   = Full rudder travel (12°)

3. Metric Conversions:
   in. x 2.54 = cm
   lb x .454 = kg

FIGURE 3 SCHEMATIC DIAGRAM OF MECHANICAL SYSTEM

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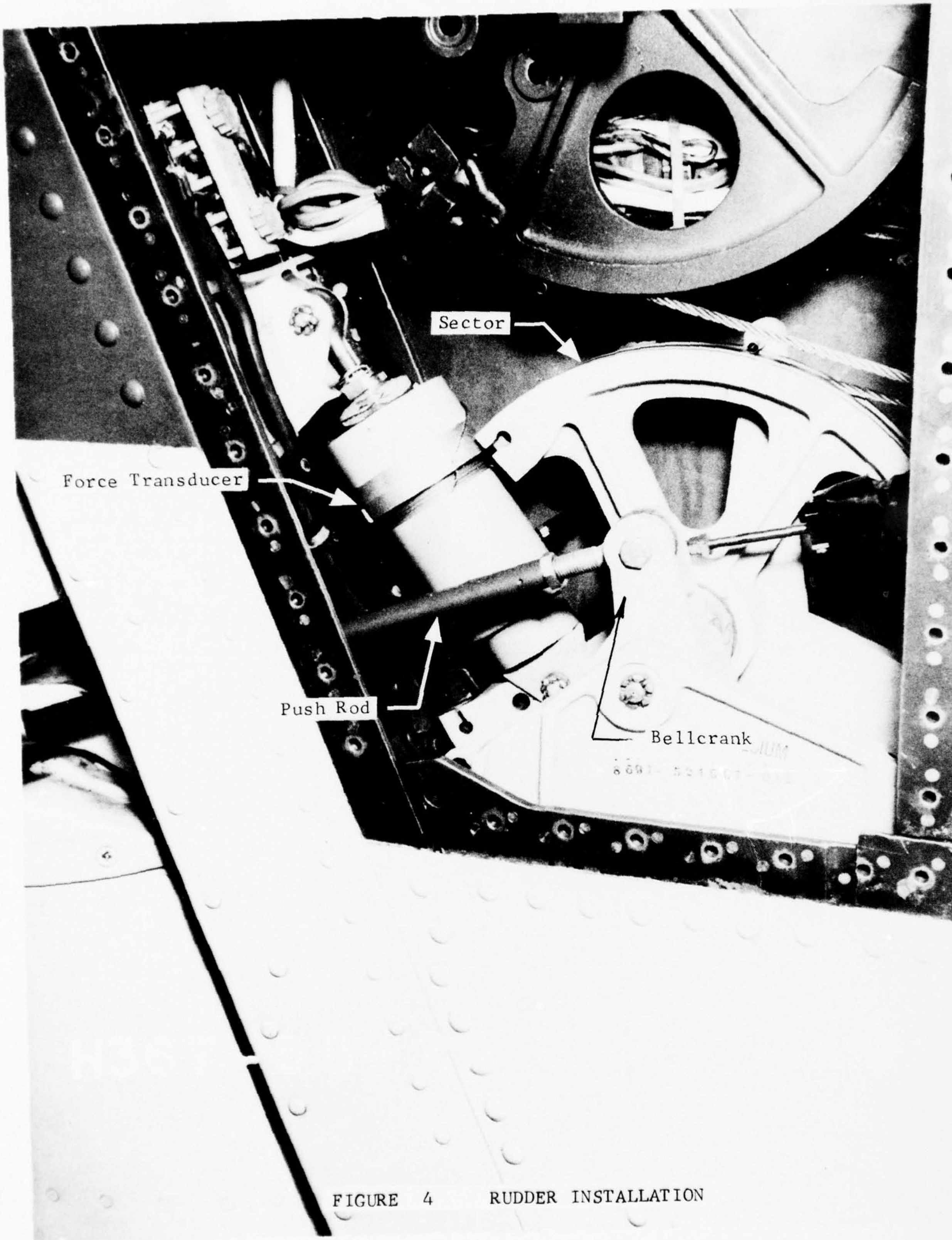
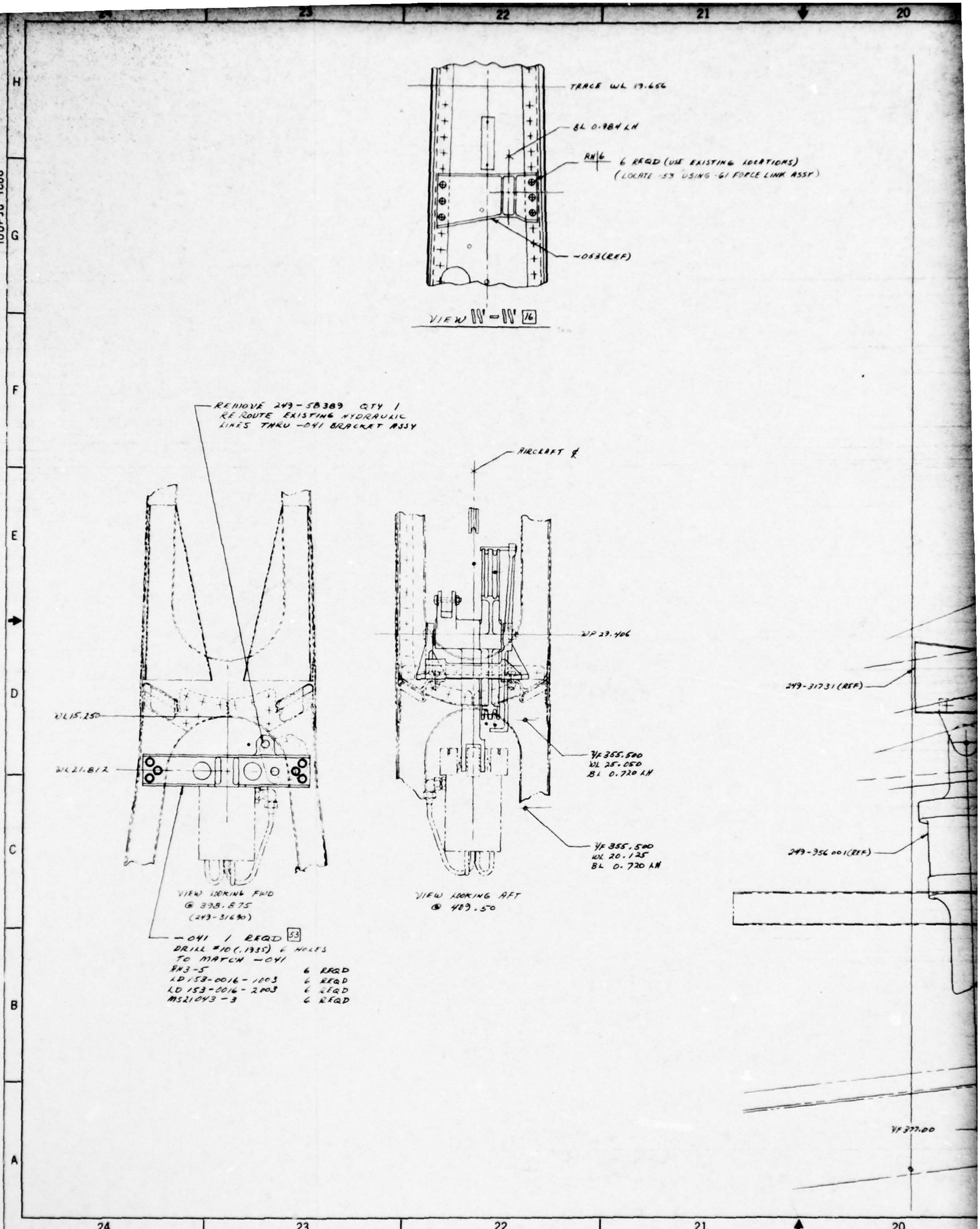


FIGURE 4 RUDDER INSTALLATION


TRACE WL 19.656
BL 0.984 LH
RH|6 6 REQD (USE EXISTING LOCATIONS)
(LOCATE -53 USING -61 FORCE LINK ASSY)
-053 (REF)
VIEW W'-W' 16
REMOVE 249-5B389 QTY 1
RE ROUTE EXISTING HYDRAULIC
LINES THRU -041 BRACKET ASSY
AIRCRAFT ℄
WP 29.406
WL 15.250
WL 21.812
249-31731 (REF)
YF 355.500
WL 25.050
BL 0.720 LH
YF 355.500
WL 20.125
BL 0.720 LH
249-356001 (REF)
VIEW LOOKING FWD
@ 398.875
(249-31690)
VIEW LOOKING AFT
@ 409.50
-041 1 REQD 53
DRILL #10 (.1935) 6 HOLES
TO MATCH -041
RH3-5 6 REQD
LD 153-0016-1003 6 REQD
LD 153-0016-2003 6 REQD
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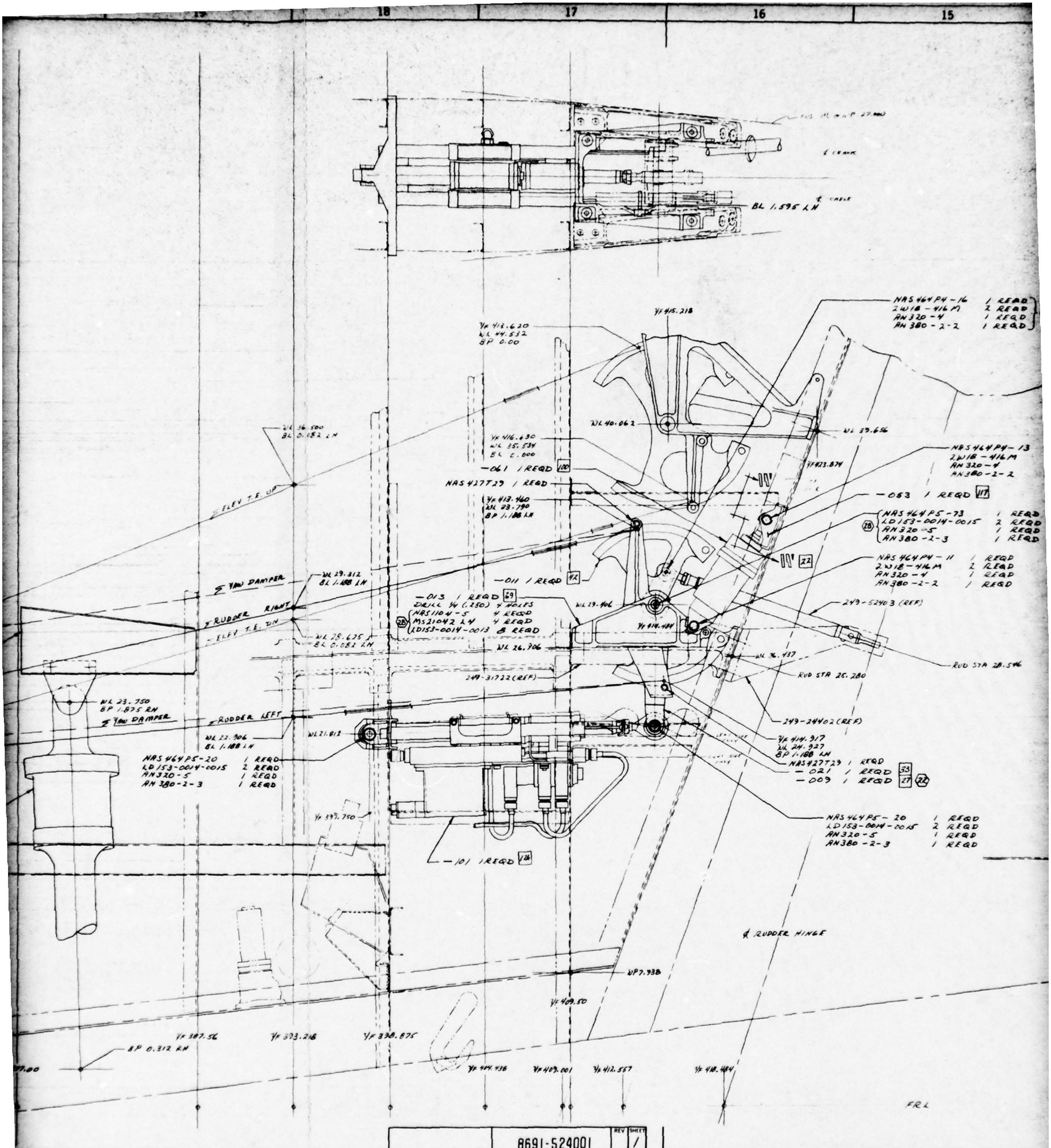

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AN380-2-2 1 REQD
YF 415.218
YF 413.620
WL 44.532
BP 0.00
WL 40.062
WL 39.656
WL 36.500
BL 0.082 LH
YF 416.630
WL 35.534
BL 0.000
-061 1 REQD 100
NAS427T29 1 REQD
YF 423.874
NAS464P4-13
2W18-416M
AN320-4
AN380-2-2
-053 1 REQD 117
YF 413.460
WL 23.790
BP 1.188 LH
ELEV T.E. UP
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AN320-5 1 REQD
AN380-2-3 1 REQD
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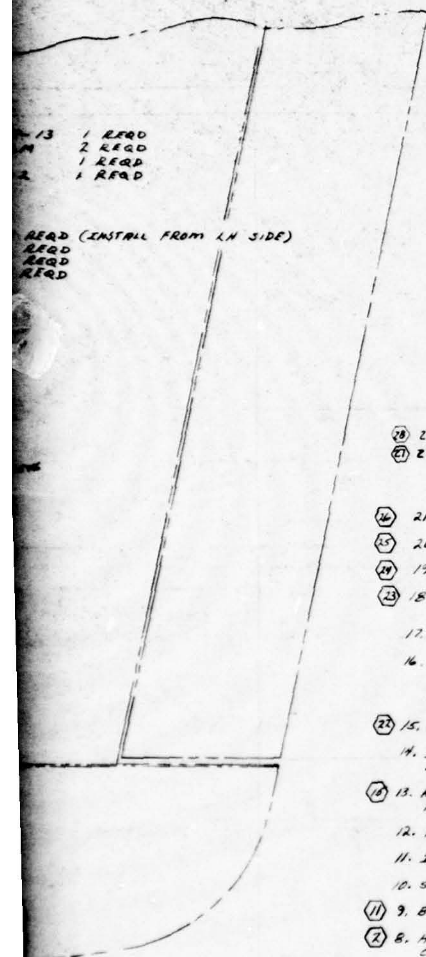
AN320-4 1 REQD
AN380-2-2 1 REQD
-011 1 REQD 42
YAW DAMPER
WL 29.312
BL 1.188 LH
-013 1 REQD 69
DRILL 1/4 (.250) 4 HOLES
NAS1104-5 4 REQD
MS21042 L4 4 REQD
LD153-0014-0013 8 REQD
RUDDER RIGHT
ELEV T.E. DN
WL 29.406
YF 414.404
249-52403 (REF)
WL 28.625
BL 0.082 LH
WL 26.906
WL 26.437
RUD STA 28.546
249-31722 (REF)
RUD STA 25.280
WL 23.750
BP 1.875 RH
YAW DAMPER
RUDDER LEFT
249-24402 (REF)
WL 22.906
BL 1.188 LH
WL 21.812
YF 414.917
WL 24.927
BP 1.188 LH
NAS427T29 1 REQD
-021 1 REQD 53
-009 1 REQD 27
NAS464P5-20 1 REQD
LD153-0014-0015 2 REQD
AN320-5 1 REQD
AN380-2-3 1 REQD
YF 397.750
NAS464P5-20 1 REQD
LD153-0014-0015 2 REQD
AN320-5 1 REQD
AN380-2-3 1 REQD
-101 1 REQD 126
RUDDER HINGE
WP 7.938
YF 409.50
YF 387.56
YF 393.218
YF 398.875
BP 0.312 RH
YF 404.438
YF 409.001
YF 412.557
YF 418.484
FRL
8691-524001
REV
SHEET
1

REQD
REQD
RQD
RQD
(28)

13 1 REQD
M 2 REQD
1 REQD
2 1 REQD

REQD (INSTALL FROM LH SIDE)
REQD
REQD
REQD



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1				111							50599	R44191P0406	REDUCER				
2				110							93190	2000 HCD	LVDT				
	1	1		109							97887	21-6-9	CRES TUBE		.025 WALL	.380 O.D	2 FT.
2				108	3						50599	R45116T0403	REDUCER				
1				107							50599	R44126-90T04	ELBOW				
	2	2		106							50599	MR44000P-04	FITTING				
			2	105							93190	FTD-1T-500	XDUCER				
				104													
4				103								MS35265-22	SCREW				
1				102								NAS1351-4H10	SCREW				
4				101								NAS1351-3H10	SCREW				
				100						4		NAS1104-5	BOLT				
			1	099								NAS699-34	CYLINDER NUT				
1				098								NAS557-24C	GROMMET				
				097						1		NAS464P5-73	BOLT				
				096						2		NAS464P5-20	BOLT				
				095						1		NAS464P4-16	BOLT				
				094						1		NAS464P4-13	BOLT				
				093						1		NAS464P4-11	BOLT				
				092						2		NAS427T29	GUARD PIN				
2				091								NAS43DD0-7	SPACER				
1				090								MS28778-6	PACKING				
1				089								MS28778-4	PACKING				
				088	1							MS28778-12	PACKING				
2				087	3							MS28778-3	PACKING				
				086	2							MS28775-212	PACKING				
1				085								MS28775-010	PACKING				
				084	4							MS28774-212	RETAINER				
1				083								MS28774-010	RETAINER				
				082					2			MS27646-43	BEARING				
				081		1						MS27643-5	BEARING				
				080				2				MS27640-5	BEARING				
				079					1			MS27640-4	BEARING				
				078						4		MS21209F1-20	HELICOIL INSERT				
4				077								MS21043-04	NUT				
3				076						6		MS21043-3	NUT				
				075						4		MS21042L4	NUT				

QUANTITY REQUIRED — MATERIAL SIZE

PARTS LIST

LAST VIEW USED W-W
LAST CODE USED (27)

(28) 23. REMOVE AND REINSTALL

(27) 22. FOR TEST INSTALLATION ON T-2C SHIP #1 UNDER G.Q.8691 CONTRACT (MODIFICATION OF CONTROLS INSTALL DWG. 249-52032). THE AIRCRAFT SHALL BE RETURNED TO ITS ORIGINAL CONFIGURATION AFTER TESTS ARE COMPLETED

(26) 21. DATE AND ASSEMBLE PER SPEC H43-5 PARA 3.2.

(25) 20. PURGE AND PROTECT PER SPEC HA0615-025.

(24) 19. ASSEMBLE PER SPEC H43-3 AND H43-5.

(23) 18. HEAT TREAT TO COND. H1050 PER SPEC ST0111LA0008.

17. UTILIZE EXISTING HARDWARE WHERE POSSIBLE.

16. ALL PRODUCTION HARDWARE, REMOVED AS A RESULT OF THIS INSTALLATION, IS TO BE IDENTIFIED, PROTECTED AND RETAINED FOR RE-INSTALLATION

(22) 15. LOCKWIRE PER SPEC LA0101-001.

14. IDENTIFY PER SPEC LA0104-003 EXCEPT DO NOT METAL IMPRESSION STAMP.

(16) 13. HEAT TREAT TO ROCKWELL C52 MIN PER SPEC MIL-H-6875 (HA0111-009).

12. RIVET CODING PER SPEC LP121-0001.

11. INSTALL RIVETS PER SPEC ST0101GA0001.

10. STANDARD DETAIL PER SPEC ST0102HA0002.

(11) 9. BLEND SMOOTHLY WITH ADJACENT SURFACES.

(2) 8. HOUSING EDGES TO BE LEFT SHARP OR BROKEN .005 MAX.

(19)(18)(3) 7. CONCENTRIC WITHIN .004 TIR.

(17) 6. CONCENTRIC WITHIN .003 TIR.

(16)(10)(9)(7)(5) 5. CONCENTRIC WITHIN .002 TIR.

(21)(14)(13)(12)(8)(6)(4)(1) 4. CONCENTRIC WITHIN .001 TIR.

3. ALL MACHINE SURFACES 125/.

2. ALL MACHINE RADIUS .062 R.

1. MACHINE PER SPEC ST0103HA0007.

NOTES: UNLESS OTHERWISE NOTED

8691-

14	13	12	11	10

2

3

THICK GAUGE	WIDTH OD/ID	LG SIZE	DRAWING OR SPECIFICATION NUMBER	ZONE
				128
				127
.025 WALL	.380 O.D	2 FT.		4/m
				90 121 124
				121
				4/m
				102
				128
				125
				125
				18
				100
				82
				15
				15 19
				15
				15
				15
				16 17
				122
				128
				128
				88
				90 121 124
				68
				127
				88
				127
				41
				56
				34 36
				48
				64
				122
				23 125 127
				18

101	081	071	061	ITEM OR FIND NO	051	041	031	021	011	BASIC	CODE IDENT	PART OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THICK GAUGE	WIDTH OD/ID	LG SIZE	DRAWING OR SPECIFICATION NUMBER	ZONE
1				074								MS24423-4	CHECK VALVE						128
				073															
				072						3		AN380-2-3	COTTER PIN						15 19
				071						3		AN380-2-2	COTTER PIN						15
				070						3		AN 320-5	NUT						15 19
				069						3		AN320-4	NUT						15
			1	068								AN316-6R	NUT						100
2				067						6		AN3-5	BOLT						23 125
				066															
				065															
1				064								7513-1032-8	BOLT						127
				063				1				457-8-272B	SPACER						36
				062						6		2W18-416M	WASHER						15
			1	061								2W1LB-84-52-90	WASHER						101
1				060								2W1LB-24-16-125	WASHER						125
4				059								2W1AL-8-16-40	WASHER						122
			1	058								IN7-16A	NUT						100
				057															
				056															
	2	2		055								LD172-0006-0001	MARKER						4/m
3				054						6		LD153-0016-2003	WASHER						23 125 127
1				053								LD153-0016-1004							125
2				052						6		LD153-0016-1003							23 125
				051						6		LD153-0014-0015							15 19
				050						8		LD153-0014-0013	WASHER						18
				049															
				048															
			1	047								NE131-0028-0002	ROD END						99
				046															
				045															
				044	1							253-58715-13	VALVE ASSY						88
				043															
				042															
				041						1		-101	ACTUATOR ASSY	MAKE FROM 504262-01					17
				040															
				039															
1				038								-081	LINE ASSY						125

26 25 24

QUANTITY REQUIRED

MATERIAL SIZE

PARTS LIST

ALTERED ITEM DRAWING

BASIC	1	
ITEM	QTY	NE
REQD PER END ITEM		

8691-524001 | REV | SHEET 1

3

12

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED
		1 MAY BE REWORKED 2 CANNOT BE REWORKED 3 RECORD CHANGE 4 NOW SHOP PRACTICE 5 PARTS MADE OK		

FIGURE 5

	101	081	071	061	ITEM OR FIND NO	051	041	031	021	011	BASIC	CODE IDENT	PART OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THKNS GAUGE	WIDTH OD/ID	LG	DRAWING OR SPECIFICATION NUMBER	ZONE
	1				037								-073	SPACER	2024-T3511 AL ALY BAR	1.00	1.00	1.03	QQ-A-200/3	128
	1				036								-071	LINK ASSY						124
					035															
	1				034								-067	SUPPORT	2024-T42 AL BARE SHT	.090	2.56	4.00	QQ-A-250/4	125
15	1				033								-065	ADJUST SCREW	E52100 STL BAR	—	.625 DIA	3.00	MIL-S-7420 COND EY	127
	1				032								-063	VALVE MODULE	MAKE FROM 504262-01-007					127
					031						1		-061	FORCE LINK ASSY						17
					030						1		-059	SHIM	2024-T42 AL BARE SHT	.090	1.00	1.00	QQ-A-250/4	70
					029															
					028															
					027						1		-053	MTG BKT	7075-T6511 EXTR AL BAR	1.25	3.50	6.00	QQ-A-200/[illegible]	15
26 25 24	1				026								-051	BY PASS VALVE ASSY						125
	1				025								-049	MTG BKT	2024-T42 AL BARE SHT	.125	2.56	[illegible]	[illegible]-A-250/4	125
				1	024								-047	FITTING	7075-T6511 EXTR AL ROD	—	2.00 DIA	[illegible]	QQ-A-200/11	100
				1	023								-045	CYLINDER	7075-T6511 EXTR AL ROD	—	2.25 DIA	4.00	QQ-A-200/11	102
				1	022								-043	NUT	7075-T6511 EXTR AL ROD	—	2.50 DIA	1.00	QQ-A-200/11	100
					021						1		-041	MTG BKT ASSY						23
				1	020								-039	SLEEVE	7075-T6511 EXTR AL ROD	—	1.75 DIA	1.50	QQ-A-200/11	102
				1	019								-037	TAILSTOCK	7075-T6511 EXTR AL ROD	—	2.00 DIA	2.00	QQ-A-200/11	103
23					018	1							-035	VALVE BODY	PH13-8MO CRES BAR	2.12	2.75	4.00	ST0160LB0013	90
23	1				017								-033	FITTING	PH13-8MO CRES ROD	—	1.00 DIA	2.25	ST0160LB0013	125
	1				016								-031	ROD ASSY	MAKE FROM 504262-01-009					125
	1				015								-029	BUSHING	BE COP ROD	—	.50 DIA	.250	LB0170-137 COND A	94
	1				014								-027	ANGLE	78F AL ALY EXTR	.094	1.00	1.00	QQ-A-200/11	122
	2				013								-025	SUPPORT	2024-T3511 AL ALY BAR	1.00	1.50	4.50	QQ-A-200/3	127
					012						1		-023	MTG BKT	7075-T6511 EXTR AL BAR	2.50	3.00	7.50	QQ-A-200/11	54
					011						1		-021	B'CRANK ASSY						16
					010			1					-019	BUSHING	BE COP ROD	—	.750 DIA	.375	LB0170-137 COND A	65
	1				009								-017	SLIDE	E4340 STL BAR	.500	.875	5.00	MIL-S-5000 COND C4	130
	1				008								-015	BLOCK	BE COP BAR	.375	1.00	1.38	LB0170-137 COND A	130
					007						1		-013	SECTOR SUPPORT	MAKE FROM 249-52405					17
					006						1		-011	SECTOR ASSY						17
					005						1		-009	NUT	7075-T651 AL ALY BAR	—	2.00 DIA	.375	QQ-A-250/9	16
					004					1			-007	SPACER	2024-T3511 AL ALY ROD	—	2.00 DIA	.250	QQ-A-200/3	42
					003				1				-005	B'CRANK	7075-T6511 EXTR AL BAR	2.00	4.00	10.50	QQ-A-200/11	36
					002					1			-003	SECTOR	7075-T73 BARE AL PLATE	1.50	5.00	5.00	H50170-015	41
					001								8691-524001	RUDDER INSTL						

QUANTITY REQUIRED — MATERIAL SIZE

PARTS LIST

HEAT TREAT 15 23 NOTED

FINISH PER SPEC 249-00024

INSPECT PER MIL-I-6870 (ST0501T0007 CLASS I)

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
MFG TOLERANCES ON:
UNDIMENSIONED ± .03
XX (DECIMALS) ± .03
XXX (DECIMALS) ± .010
ANGLES ± 30'
HOLES NOTED DRILL
013 THRU .040 +.001 -.001
.041 THRU .130 +.002 -.001
.131 THRU .229 +.003 -.001
.230 THRU .500 +.004 -.001
.501 THRU .750 +.005 -.001
.751 THRU 1.000 +.007 -.001
1.001 THRU 2.000 +.010 -.001
DO NOT SCALE PRINT

NEXT ASSY	USED ON	END ITEM NO	THRU
21	G.D. 8651	TEST	—
APPLICATION		EFFECTIVITY	

CONTR NO.
DWN BY GRIESEMER 3-7-77
CHK BY [illegible]
APVD L. BIAFORE [illegible]

Columbus Aircraft Division
North American Rockwell
COLUMBUS, OHIO 43216

RUDDER INSTALLATION - ADVANCED FLIGHT CONTROL ACTUATION SYSTEM

SIZE J CODE IDENT NO 89372 8691-524001

SCALE 1/1 & NOTED SHEET 1 OF 6

FORM 311 G4 REV 11-72

8691-524001

The relationship between pedal force and rudder travel is approximately 7.5 lb/deg (33.3 N/deg) of rudder movement or 90 lb (.4 kN) for full travel (12°). Pedal displacement was small, approximately .50 in. (13mm), since the force transducer length changed only 0.025 in. (0.63mm) for full rudder travel (pedal displacement was due primarily to cable stretch). In the original manual control system, pedal displacement was approximately 4 in. (10.2 cm) for full rudder travel (25°).

The maximum hinge moment normally applied to the T-2C rudder is based on pilot strength and is 2200 lb-in (249 N-m). Maximum rudder deflection a pilot can achieve thus depends on air loads present. The AFCAS rudder actuator can develop 13,000 lb-in (1470 N-m). Because of the limited rudder deflection (12° max.) the high moment capability of the rudder actuator required only minor adjustment in the T-2C flight envelope to assure safety.

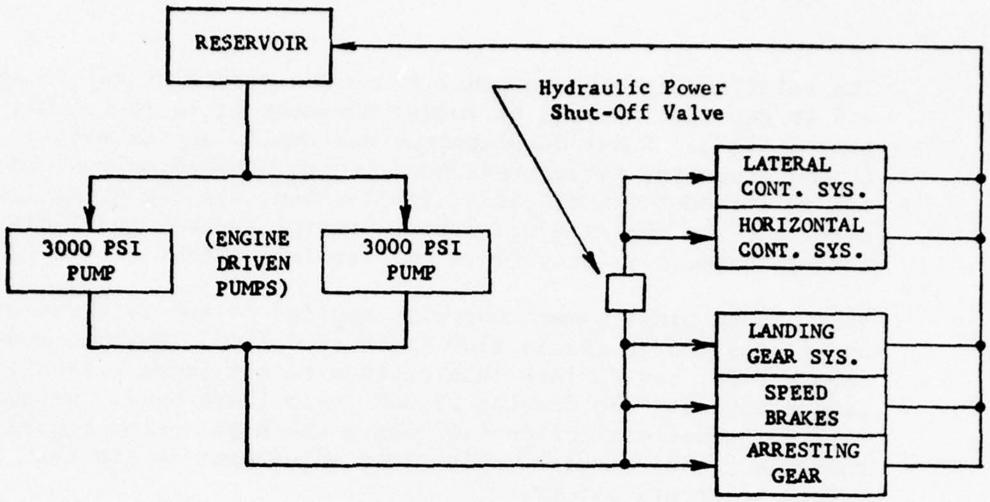
3.3 HYDRAULIC SYSTEM

3.3.1 System Description

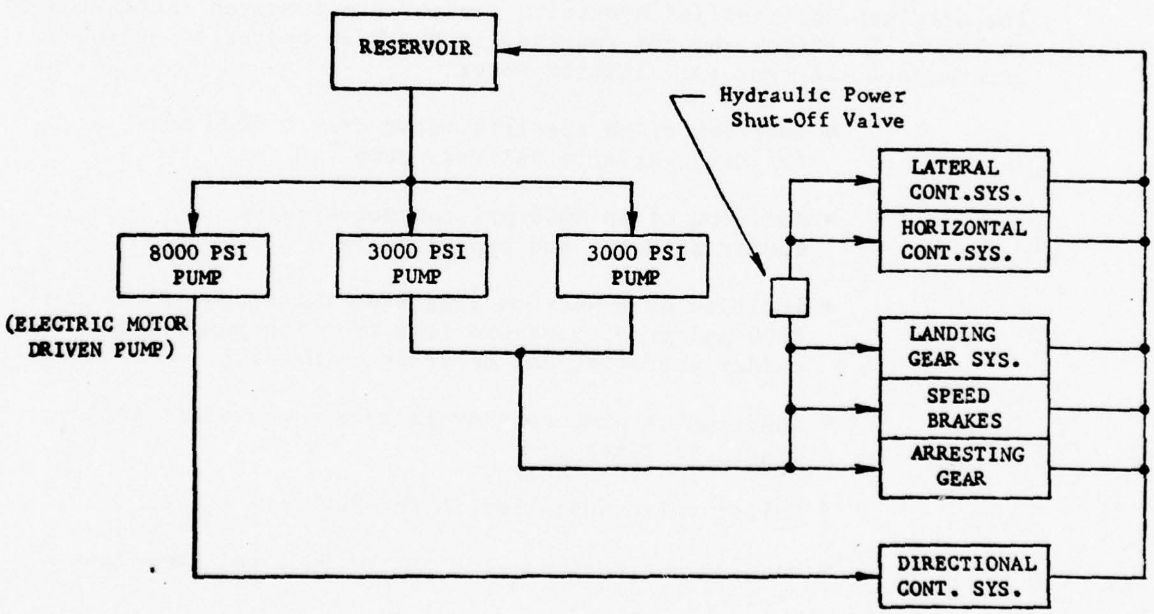
The original and modified hydraulic systems are compared schematically on Figure 6. Major changes required in the T-2C hydraulic system to accommodate the test installation were:

- Addition of an electric motor driven 8000 psi (55 MPa) variable delivery pump
- Addition of an 8000 psi control-by-wire rudder actuator and bypass valve
- Addition of a suction line from the reservoir to the 8000 psi pump, pressure line from the pump to the rudder actuator, and actuator return line
- Addition of pump case drain return and shaft seal overboard lines
- Relief valve installed in the 8000 psi system
- Heat exchanger installed in the 8000 psi pump case drain line

The modified system is shown schematically on Figure 7; 8000 psi components are listed on Table I. The 3000 psi (21 MPa) and 8000 psi (55 MPa) systems shared a common reservoir and common return lines. All major components, except for the rudder actuator, were located in the fuselage compartment above the engines. Plumbing details are given on Figure 8.



ORIGINAL 3000 PSI SYSTEM



MODIFIED HYDRAULIC SYSTEM

FIGURE 6 ORIGINAL AND MODIFIED HYDRAULIC SYSTEMS

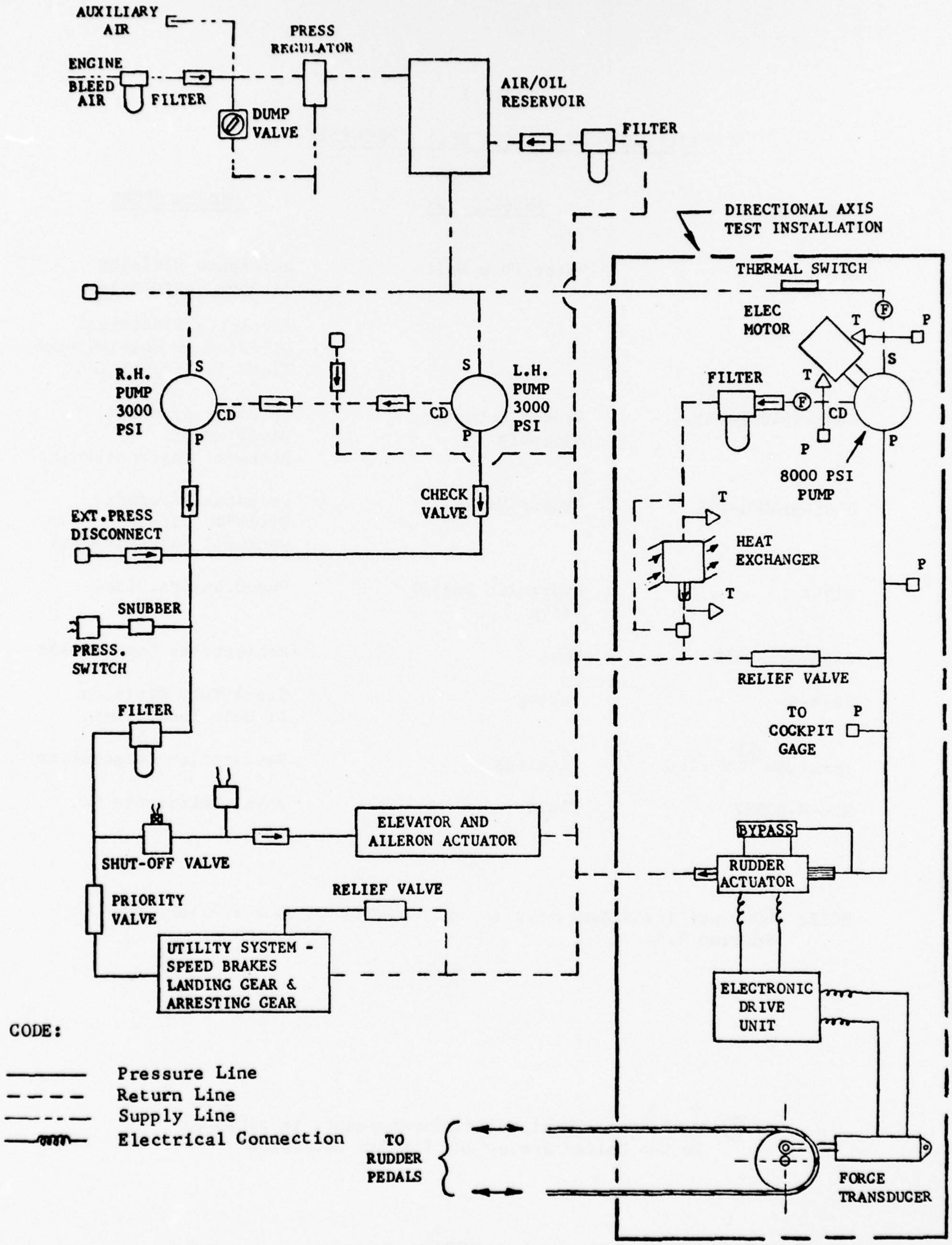


FIGURE 7 SCHEMATIC DIAGRAM OF MODIFIED HYDRAULIC SYSTEM

TABLE I

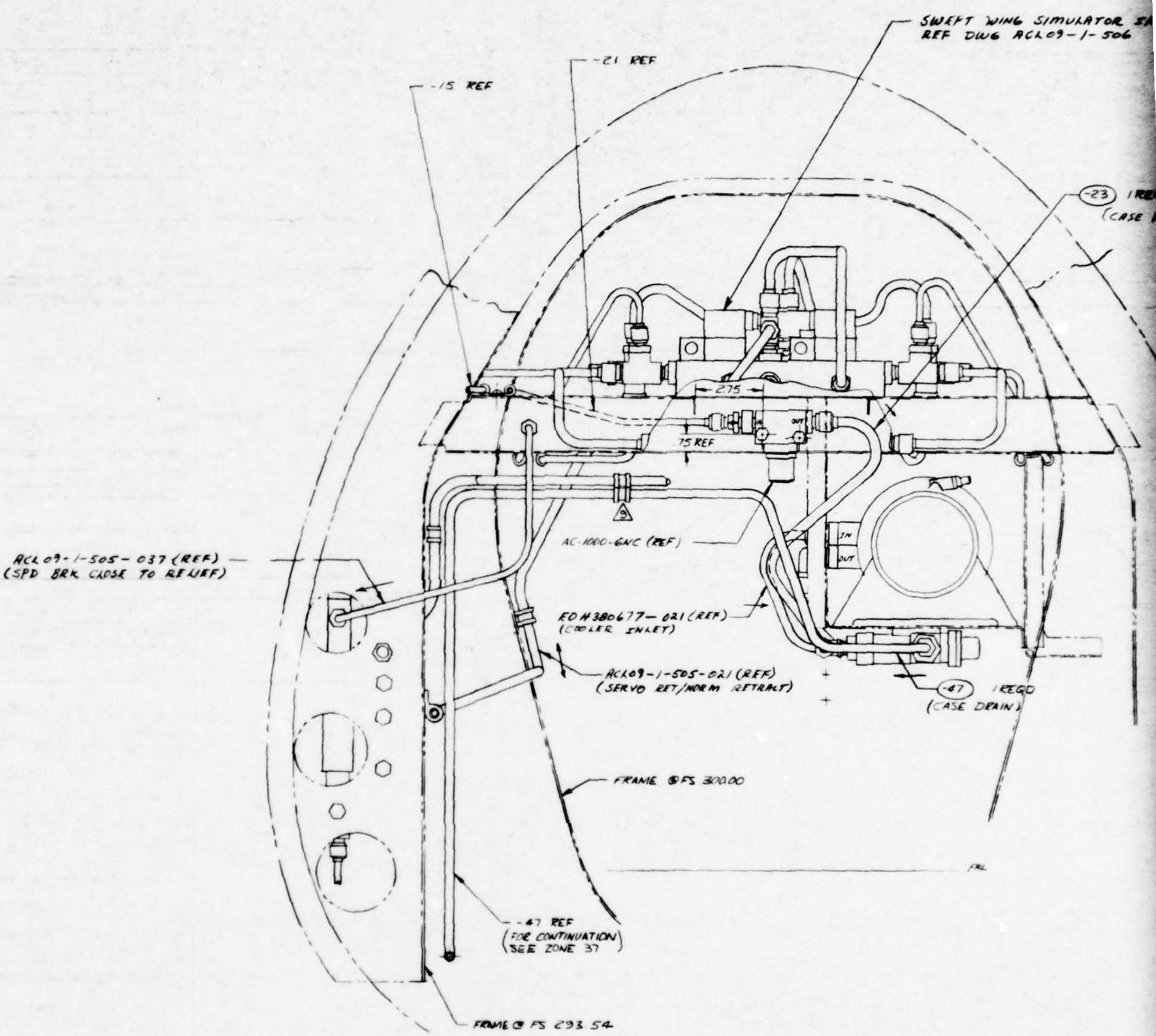
LIST OF 8000 PSI (55 MPa) COMPONENTS

PART NO.	DESCRIPTION	MANUFACTURER
66059	Motor/Pump Unit	Aerospace Division of Abex Corporation Aerospace Electrical Division of Westinghouse Electric Corporation
8691-524001-101	Rudder Actuator Assembly	Columbus Aircraft Division of Rockwell International
8691-524001-051	Bypass Valve	Columbus Aircraft Division of Rockwell International
1180A	Hydraulic Relief Valve	PneuDraulics, Inc.
R44598-6-0310	Hose	Resistoflex Corporation
21-6-9	Tubing	Trent Tube Division of Colt Industries
Dynatube® Series	Fittings	Resistoflex Corporation
MIL-H-83282	Fluid	Royal Lubricants Co.

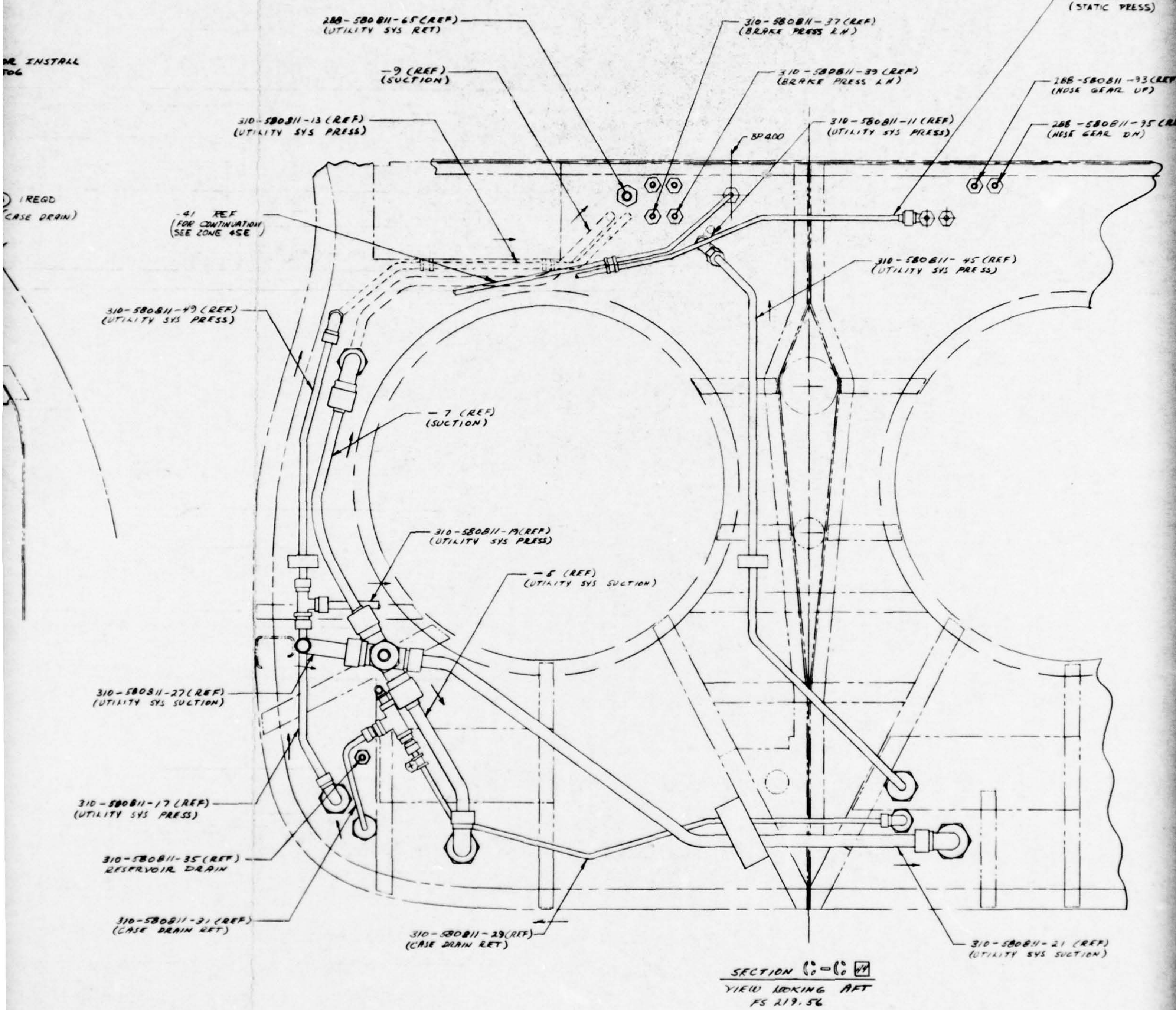
NOTE: 8000 psi instrumentation is not included in this listing, see Section 3.5.

® Dynatube, a Resistoflex development, is patented in the United States and foreign countries

010082-1888

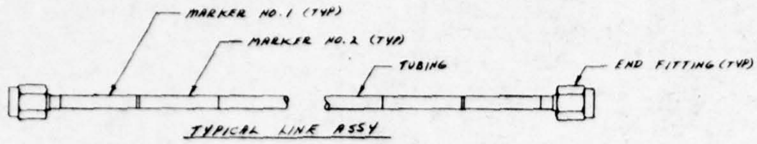


SECTION A-A
VIEW LOOKING AFT
FS 293.54



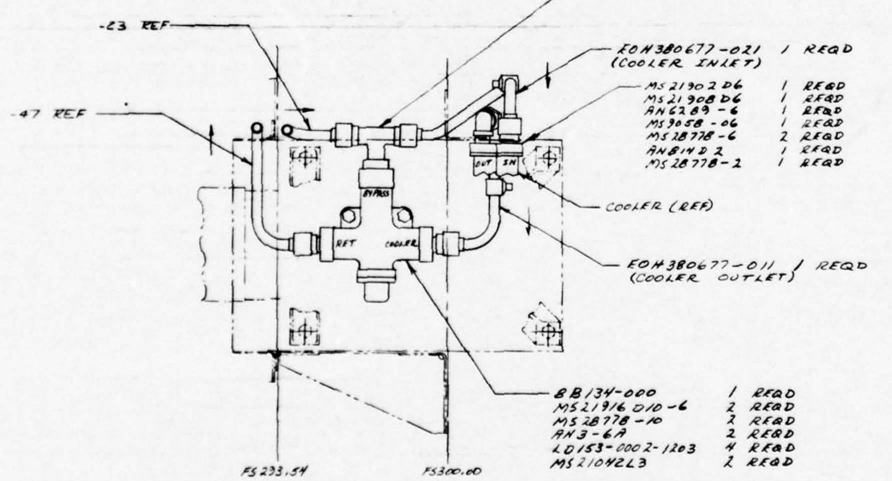
8691-580010	REV	SHEET 1

19	18	17	16	15



TYPICAL LINE ASSY

DASH NO. ASSY	DASH NO. LINE	END FITTING	TUBING MATERIAL	TUBING WALL	TUBING OD	LG	MARKERS NO. 1	MARKERS NO. 2
-3	-103	MS21921-10D MS21922-10	6061-T6 AL ALY MIL-T-7081	.049	.625	3	LD172-0006-0001	LD172-0006-0004
-5	-105	MS21921-10D MS21922-10	6061-T6 AL ALY MIL-T-7081	.049	.625			LD172-0006-0004
-7	-107	MS21921-8D MS21922-8	6061-T6 AL ALY MIL-T-7081	.049	.500			LD172-0006-0004
-9	-109	MS21921-8 MS21922-8	304 CRES MIL-T-6845	.035	.500			LD172-0006-0004
-11	-111	MS21921-8 MS21922-8	304 CRES MIL-T-6845	.035	.500			LD172-0006-0004
-13	-113	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-15	-115	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-17	-117	MS21921-8D MS21922-8	6061-T6 AL ALY MIL-T-7081	.049	.500		LD172-0006-0001	LD172-0006-0004
-19	-119	MS21921D4 MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250			LD172-0011-0012
-21	-121	MS21921-4D MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250		LD172-0006-0001	LD172-0006-0159
-23	-123	MS21921-6D MS21922-6	6061-T6 AL ALY MIL-T-7081	.049	.375			LD172-0006-0159
-25	-125	MR44000P-04 MRS4100T-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-27	-127	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-29	-129	MS21921-4D MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250			LD172-0006-0105
-31	-131	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-33	-133	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-35	-135	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-37	-137	MS21921-4D MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250			LD172-0006-0041
-39	-139	MS21921-4D MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250			LD172-0006-0041
-41	-141	MS21921-4D MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250			LD172-0006-0041
-43	-143	MS21921-6D MS21922-6	6061-T6 AL ALY MIL-T-7081	.049	.375			LD172-0006-0041
-45	-145	MS21921-6D MS21922-6	6061-T6 AL ALY MIL-T-7081	.049	.375			LD172-0006-0159
-47	-147	MS21921-6D MS21922-6	6061-T6 AL ALY MIL-T-7081	.049	.375			LD172-0006-0159
-49	-149	MR44000P-04	21-6-9 CRES AMS 5561	.025	.250			LD172-0006-0127
-51	-151	MS21921-4 MS21922-4	304 CRES MIL-T-6845	.020	.250			LD172-0006-0142
-53	-153	MS21921-4D MS21922-4	6061-T6 AL ALY MIL-T-7081	.035	.250	3	LD172-0006-0001	LD172-0006-0143



SECTION 13-13 36

- .75 REF
- S)
- 3 (REF)
- P)
- 5 (REF)

1	
DG22	1
-263	1
-3	1
-1203	2

Flag 2	
DG10	1
—	-
—	-

Flag 3	
DG18	1
—	-
—	-

Flag 4	
DG10	1
DG4	1
-263	1
-3	1
-1203	2

Flag 5	
DG6	2
-263	1
-3	1
-1203	2

SEE SHT 3 FOR

	ITEM OR FIND NO.	QUANTITY REQUIRED					BASIC	CODE IDENT	PART OR IDENTIFYING NUMBER
	119								
	118						2		MS28778-10
	117						16		-6
	116						6		-4
	115						1		MS28778-2
	114								
	113						2		MS28773-06
	112						2		MS28773-04
	111								
2	110						1		AC-1000-6NC
2	109						1		PQ76-0486
	108								
2	107						1	06177	1180A
	106						2		211-35-000
	105						1		R05-F-295
	104						1		BB134-000
2	103						1		5B300
	102								
2	101						1	50599	R44359P-06
	100						1	50599	R44191P-0406
	099						1	50599	R44182P-06
	098						2	50599	R44182P-04
	097						1	50599	R44133T-04
	096						1	50599	R44118T-06
	095						2	50599	R44111T-04
2	094						1	50599	MRS4100T-04
	093								
2	092						15	50599	MR44000P-04
	091								
	090								
	089								
	088						3		MS21919DG22
	087						3		DG18
	086						5		DG10
	085						1		DG8
	084						4		DG6
	083						15		MS21919DG4
	082								
	081						1		MS21910-6
	080						2		MS21916D10-6
	079						2		MS21916D6-4
	078						1		MS21914-4D
	077						1		MS21912-4
	076						1		MS21909D6
	075						1		MS21909D4

PART

8691-580010

2

3

8	7	6	5	4

518 | 1

DG4 -263 -3 -1203 | 1 1 1 2

DG4 | 1

DG8 -263 -3 -1203 | 1 1 1 2

DG4 -263 -3 -1203 | 2 1 1 2

(4) 10. FOR TEST INSTALLATION ON T-2C SHIP#1 UNDER G.O. B651 CONTRACT. (MODIFICATION OF HYD INSTALL DWG 310-58001A) THE AIRCRAFT SHALL BE RETURNED TO ITS ORIGINAL CONFIGURATION AFTER TESTS ARE COMPLETED.

9. THIS BLOCK DENOTES CALLOUTS FOR CLAMP INSTALL.

CODE FOR DUPLICATION

CLAMP	DG	MS21919DG( )
SCREW		MS35207-263
NUT	-3	MS21042L3
WASHER		LD153-0006-1203
SPACER		NAS43DD-3-( )

NUMBER REQD

8. INSTALL FITTINGS AND TUBE ASSYS PER SPEC FA6-20.

7. INSTALL THREADED FASTENERS PER SPEC LA0101-001.

6. INSTALL IDENTIFICATION TAPE PER SPEC LA0104-005.

5. IDENTIFY PER SPEC LA0104-003 EXCEPT DO NOT METAL IMPRESSION STAMP.

4. FABRICATE TUBING PER SPEC FA6-159.

(3) 3. TO BE DETERMINED AT INSTALLATION.

(2) 2. TO BE SUPPLIED BY ENGINEERING.

(1) 1. ALL PRODUCTION HARDWARE, REMOVED AS A RESULT OF THE INCORPORATION OF THIS TEST INSTALLATION, TO BE IDENTIFIED, PROTECTED AND RETAINED FOR RE-INSTALLATION.

NOTES: UNLESS OTHERWISE NOTED

...HT 3 FOR PL CONTINUATION

...OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THICK GAUGE (MATERIAL)	WIDTH OD/ID (MATERIAL)	LG (SIZE)	DRAWING OR SPECIFICATION NUMBER	ZONE
28778-10	PACKING						
-6							
-4							
28778-2	PACKING						
28773-06	RETAINER						
28773-04	RETAINER						
1000-6NC	FILTER						36
76-0486	MOTOR / PUMP						52
							41
0A	RELIEF VALVE						38
-35-000	PRESSURE XDUCER						37 38
5-F-295	HOSE						36
134-000	THERMAL BY PASS						11
300	COOLER						36
							41
4359P-06	ELBOW						38
191P-0406	CONNECTOR						41
182P-06	CONNECTOR						55
182P-04	CONNECTOR						38
133T-04	TEE						38
118T-06	NUT						41
111T-04	TEE						27/36
4100T-04	CONNECTOR						13
							13
4000P-04	FITTING						13
							13
919DG22	CLAMP						
DG18							
DG10							
DG8							
DG6							
919DG4	CLAMP						
910-6	TEE						
916D10-6	REDUCER						
16D6-4	REDUCER						36
914-4D	CAP						41
12-4	TEE						
09D6	TEE						
9D4	TEE						

PARTS LIST

ITEM OR FIND NO.	QUANTITY REQUIRED (BASIC)	CODE IDENT	PART OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THICK GAUGE (MATERIAL)	WIDTH OD/ID (MATERIAL)	LG (SIZE)	DRAWING OR SPECIFICATION NUMBER	ZONE
074	1		MS21908D6	ELBOW						11
073	2		MS21908-8	ELBOW						
072	1		MS21908D4	ELBOW						
071	1		MS21908-4	ELBOW						
070	1		MS21907D4	ELBOW						
069	1		MS21902-8	UNION						
068	3		MS21902-6	UNION						
067	2		MS21902D6	UNION						
066	1		MS21902D4	UNION						
065	2		MS21042L4	NUT						36
064	27		MS21042L3	NUT						
063	3		MS9058-06	BACKUP						
062										36
061	1		AN893-2D	BUSHING						36
060	5		AN6289-6	NUT						
059	2		AN6289-4	NUT						
058	1		AN937D6	CROSS						
057	2		AN924-8D	NUT						
056	3		AN924-4D	NUT						
055	4		AN901-8A	WASHER						
054	2		AN901-6A	WASHER						
053	5		AN901-4A	WASHER						11
052	1		AN814-6	PLUG						41
051	1		AN814D2	PLUG						11
050	2		AN4-24A	BOLT						36
049	2		AN3-6A	BOLT						
048	4		AN3-5A	BOLT						12
047	4		LD172-0006-0139	MARKER						12
046	10		-0127							12
045	2		-0105							12
044	8		-0041							12
043	12		-0004							12
042	6		-0002							41
041	42		LD172-0006-0001	MARKER						36
040										
039	4		LD153-0002-1204	WASHER						
038	54		LD153-0002-1203	WASHER						

PARTS LIST

LAST CODES USED: (5) (9)

BASIC	1	(4)	G.O. B...
ITEM	QTY	NEXT ASSY	USE...
REQD PER END ITEM		APPLICATION	

...80010 | REV | SHEET 1

9	8	7	6	5	4

3

4

REVISIONS					
ZONE	LTR	DESCRIPTION	DISPN	DATE	APPROVED
		1. MAY BE REWORKED 2. CANNOT BE REWORKED 3. RECORD CHANGE 4. NOW SHOP PRACTICE 5. PARTS MADE OK			

FIGURE 8

ITEM OR FIND NO.	QUANTITY REQUIRED	CODE IDENT	PART OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THKNS GAUGE	WIDTH OD/ID	LG	DRAWING OR SPECIFICATION NUMBER	ZONE
037	1		HE273-0018-0003	TEE						
036	1		HE273-0007-0011	TEE						43
035										
034	1		2C12-2	CLIP						34
② 033	1		EDH380677-021	LINE ASSY.						11
032	1		EDH380677-011							11
031	1		504266-03-012							37
030	1		504266-03-011							40
029										
028										39
② 027	1		504266-02-010	LINE ASSY						38
026										
025	1		8691-580010-49	LINE ASSY						38
024	1		-47							20
023	1		-45							38
022	1		-43							48
021	1		-41							45
020	1		-39							41
019	1		-37							56
018	1		-35							40
017	1		-33							39
016	1		-31							21
015	1		-29							27
014	1		-27							27
013	1		-25							28
012	1		-23							20
011	1		-21							54
010	1		-19							46
009	1		-17							57
008	1		-15							34
007	1		-13							39
006	1		-11							42
005	1		-9							43
004	1		-7							44
003	1		-5							44
002	1		-3	LINE ASSY						46
001			8691-580010	HYD EQUIP INSTALL						

PARTS LIST

8691-580010

NEXT ASSY	USED ON	END ITEM NO.	THRU
④	GD 8691	TEST	—
APPLICATION		EFFECTIVITY	

HEAT TREAT

FINISH

INSPECT PER MIL-I-6870 (ST0501LT0007 CLASS II) ⑤

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
MFG TOLERANCES ON:
UNDIMENSIONED ±.03
XX (DECIMALS) ±.03
XXX (DECIMALS) ±.010
ANGLES ±30'
HOLES NOTED "DRILL"
.013 THRU .040 +.001 -.001
.041 THRU .130 +.002 -.001
.131 THRU .229 +.003 -.001
.230 THRU .500 +.004 -.001
.501 THRU .750 +.005 -.001
.751 THRU 1.000 +.007 -.001
1.001 THRU 2.000 +.010 -.001
DO NOT SCALE PRINT

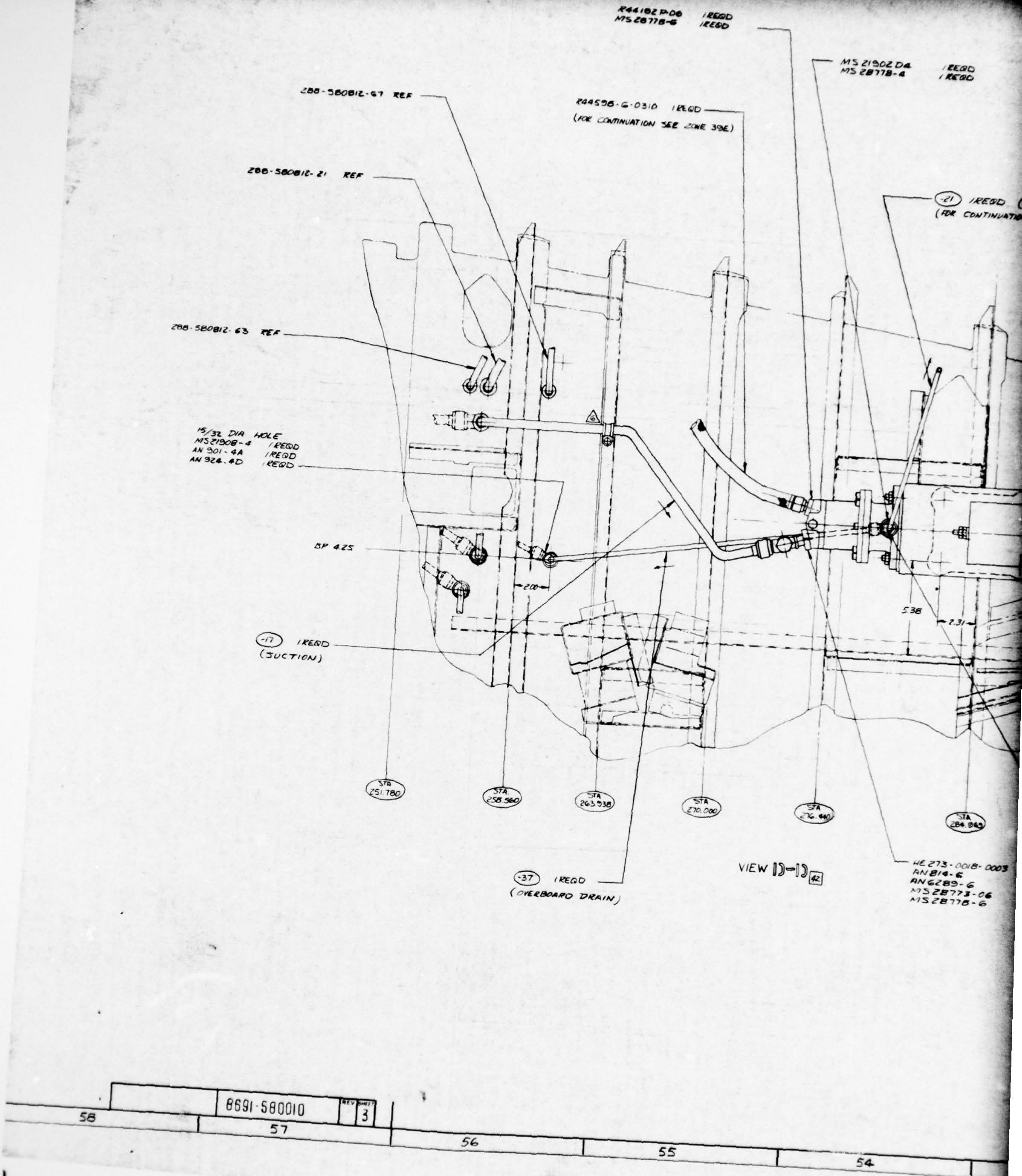
CONTR NO
DWN BY Swisterer 3-29-77
CHK BY R Holland 12-21-77
APVD L. Biarge 12-22-77

Columbus Division
North American Rockwell
COLUMBUS, OHIO 43216

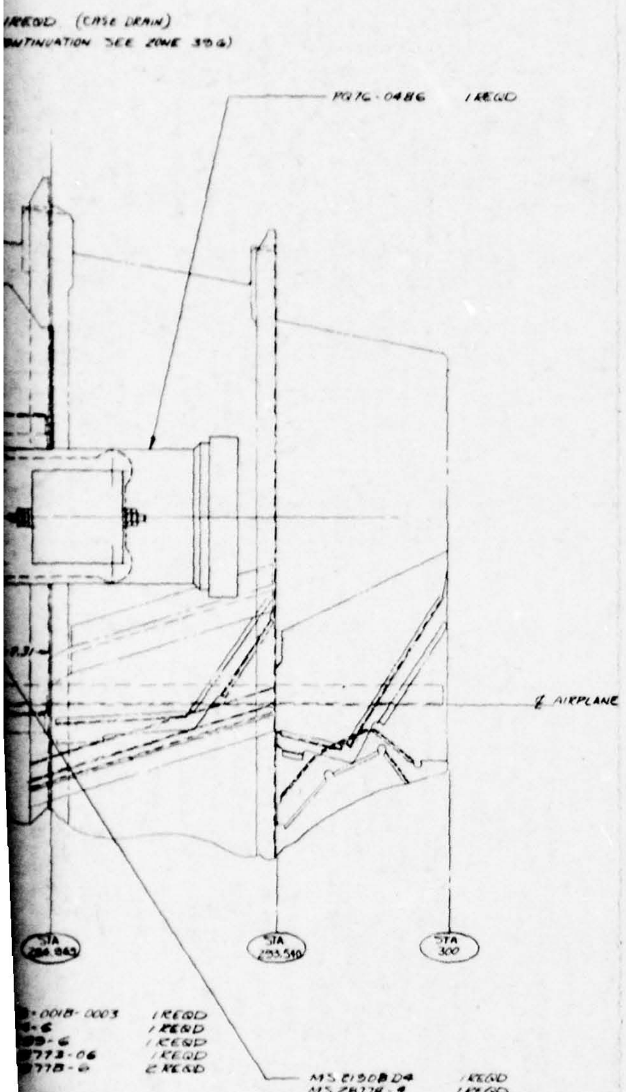
HYDRAULIC EQUIPMENT INSTL — 8000 PSI RUDDER

SIZE J | CODE IDENT NO. 89372 | 8691-580010

SCALE 1/2 | SHEET 1 OF 3


R44182 P-06 1REQD
MS28778-6 1REQD
MS21902D4 1REQD
MS28778-4 1REQD
288-580812-67 REF
R44598-6-0310 1REQD
(FOR CONTINUATION SEE ZONE 39E)
288-580812-21 REF
-21 1REQD
(FOR CONTINUATIO
288-580812-63 REF
15/32 DIA HOLE
MS21908-4 1REQD
AN901-4A 1REQD
AN924-4D 1REQD
BP 4.25
2.00
5.38
2.31
-17 1REQD
(SUCTION)
STA 251.780
STA 258.560
STA 263.938
STA 270.000
STA 276.440
STA 284.965
VIEW D-D
HE273-0018-0003
AN814-6
AN6289-6
MS28773-06
MS28778-6
-37 1REQD
(OVERBOARD DRAIN)
8691-580010
3
58
57
56
55
54

REVISIONS		
DESCRIPTION	DATE	APPROVED
1. MAY BE REWORKED 2. CANNOT BE REWORKED 3. RECORD CHANGE 4. NEW SHOP PRACTICE 5. PARTS MADE OK		



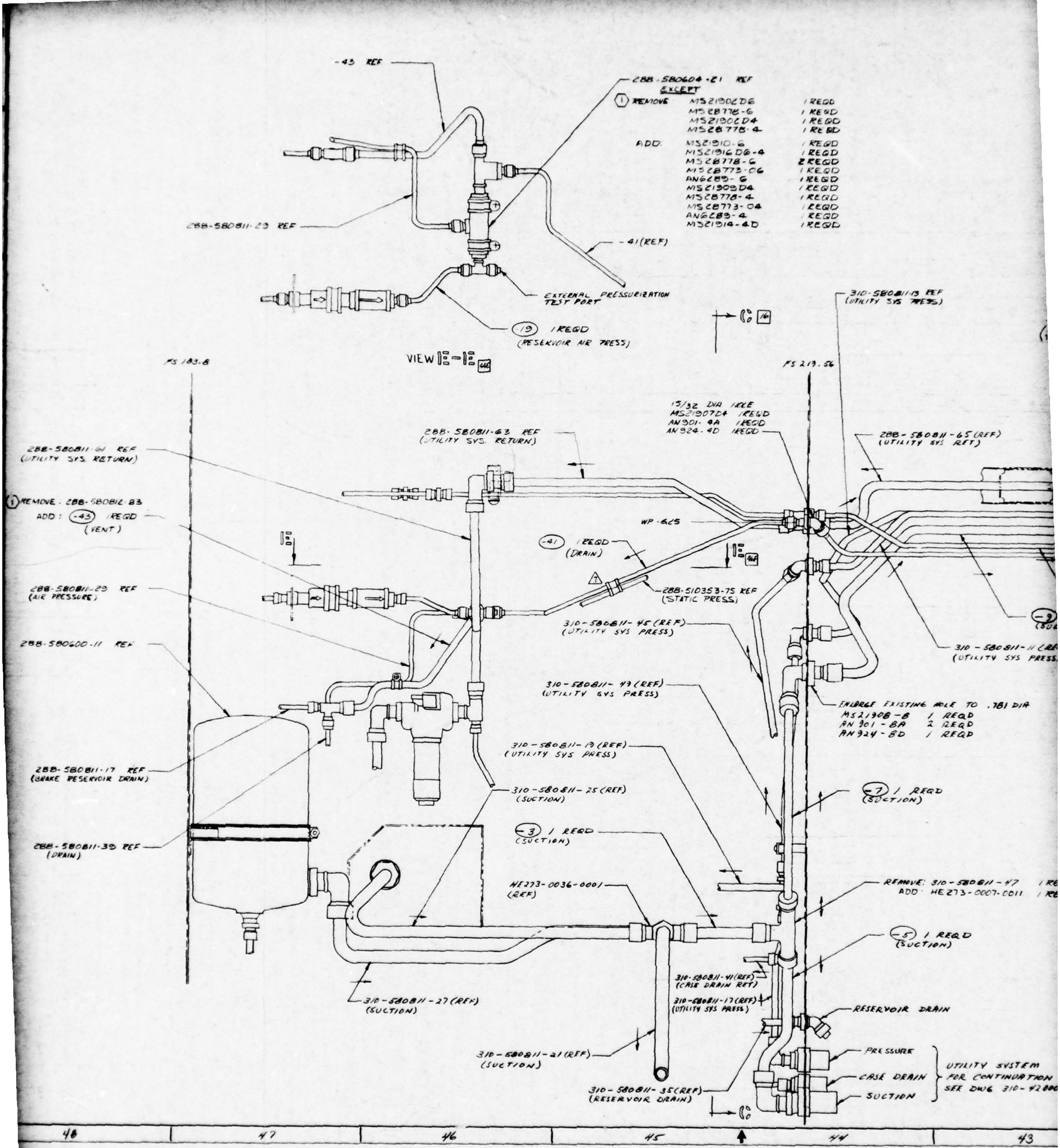
	ITEM OR FIND NO.	QUANTITY REQUIRED	CODE IDENT	PART OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THICK GAUGE	WIDTH OD/ID	LG SIZE	DRAWING OR SPECIFICATION NUMBER	ZONE
2		1	50599	R4459B-6-0310	HOSE						
2		1	50599	R44362T-04	TEE						
2		1	50599	R44118T-04	NUT						
		1		-75	BRACKET	2024 AL CLAD SHEET	063	2.31	2.50	QQ-A-250/5	
		1		-73	BRACKET	2024 AL CLAD SHEET	063	2.00	2.68	QQ-A-250/5	25
		1		-53	LINE ASSY						
		1		-51	LINE ASSY						
		2		NAS43DD4-40	SPACER						
		2		MS35842-16	CLAMP						
		13		MS35207-263	SCREW						
		2		MS35207-261	SCREW						
		1		MS24423-6	CHECK VALVE						38
		1		MS24423-4	CHECK VALVE						36
		1		MS21924D6	UNION						
		4		MS21922-10	SLEEVE						
		8		-8							
		8		-6							
		14		MS21922-4	SLEEVE						
		4		MS21921-10D	NUT						
		4		-8D							
		4		-8							
		8		-6D							
		2		-4							
		12		MS21921-4D	NUT						

PARTS LIST

SIZE	CODE IDENT NO	
J	89372	8691-580010
SCALE 1/2		SHEET 3

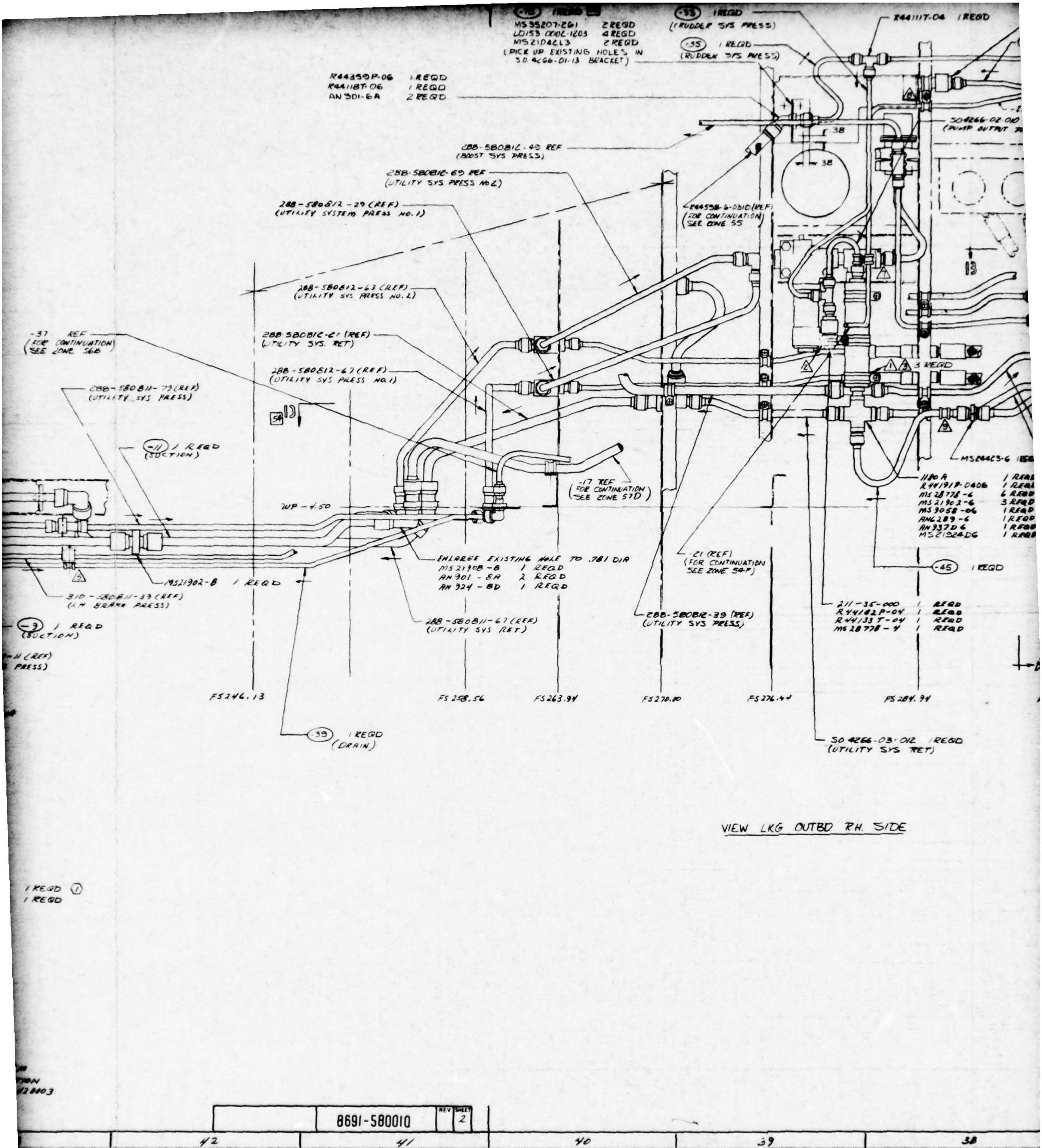
53 52 51 50 49 6

FORM 311 G 14 REV 2-70

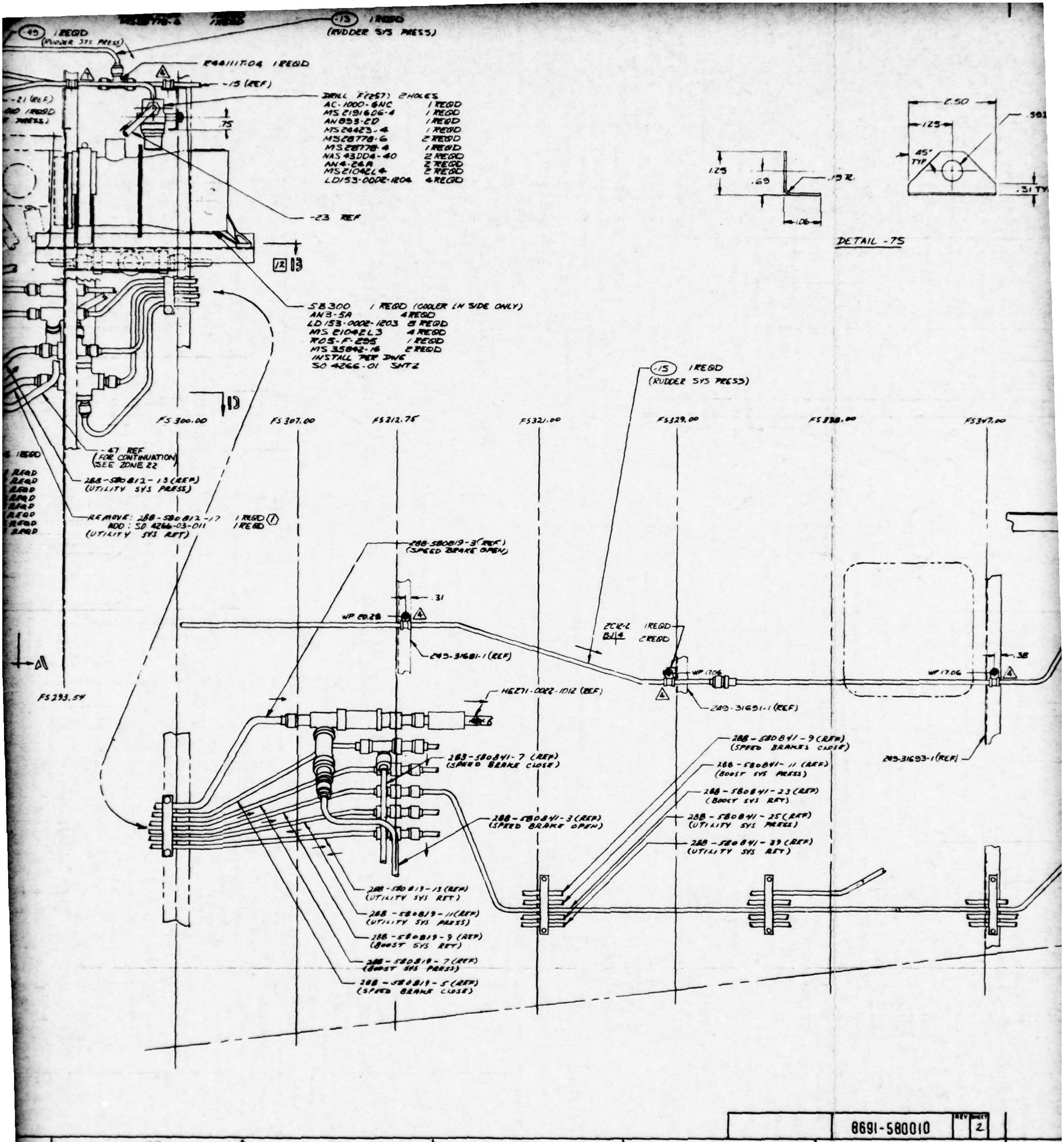


-43 REF
288-580604-21 REF
EXCEPT
1 REMOVE MS21902D6 1 REQD
MS28778-6 1 REQD
MS21902D4 1 REQD
MS28778-4 1 REQD
ADD: MS21910-6 1 REQD
MS21916D6-4 1 REQD
MS28778-6 2 REQD
MS28773-06 1 REQD
AN6289-6 1 REQD
MS21909D4 1 REQD
MS28778-4 1 REQD
MS28773-04 1 REQD
AN6289-4 1 REQD
MS21914-4D 1 REQD
288-580811-29 REF
-41 (REF)
EXTERNAL PRESSURIZATION TEST PORT
19 1 REQD
(RESERVOIR AIR PRESS)
VIEW
310-580811-13 REF
(UTILITY SYS PRESS)
FS 183.8
FS 219.56
15/32 DIA HOLE
MS21907D4 1 REQD
AN901-4A 1 REQD
AN924-4D 1 REQD
288-580811-63 REF
(UTILITY SYS. RETURN)
288-580811-65 (REF)
(UTILITY SYS RET)
288-580811-61 REF
(UTILITY SYS RETURN)
1 REMOVE: 288-580812-83
ADD: -43 1 REQD
(VENT)
WP-625
-41 1 REQD
(DRAIN)
288-510353-75 REF
(STATIC PRESS)
288-580811-29 REF
(AIR PRESSURE)
310-580811-45 (REF)
(UTILITY SYS PRESS)
288-580600-11 REF
310-580811-11 (REF)
(UTILITY SYS PRESS)
310-580811-49 (REF)
(UTILITY SYS PRESS)
ENLARGE EXISTING HOLE TO .781 DIA
MS21908-8 1 REQD
AN901-8A 2 REQD
AN924-8D 1 REQD
310-580811-19 (REF)
(UTILITY SYS PRESS)
288-580811-17 REF
(BRAKE RESERVOIR DRAIN)
310-580811-25 (REF)
(SUCTION)
-7 1 REQD
(SUCTION)
288-580811-39 REF
(DRAIN)
-3 1 REQD
(SUCTION)
HE273-0036-0001
(REF)
REMOVE: 310-580811-47 1 REQD
ADD: HE273-0007-0011 1 REQD
-5 1 REQD
(SUCTION)
310-580811-41 (REF)
(CASE DRAIN RET)
310-580811-17 (REF)
(UTILITY SYS PRESS)
310-580811-27 (REF)
(SUCTION)
RESERVOIR DRAIN
310-580811-21 (REF)
(SUCTION)
PRESSURE
CASE DRAIN
SUCTION
UTILITY SYSTEM
FOR CONTINUATION
SEE DWG 310-42800
310-580811-35 (REF)
(RESERVOIR DRAIN)
48
47
46
45
44
43

2

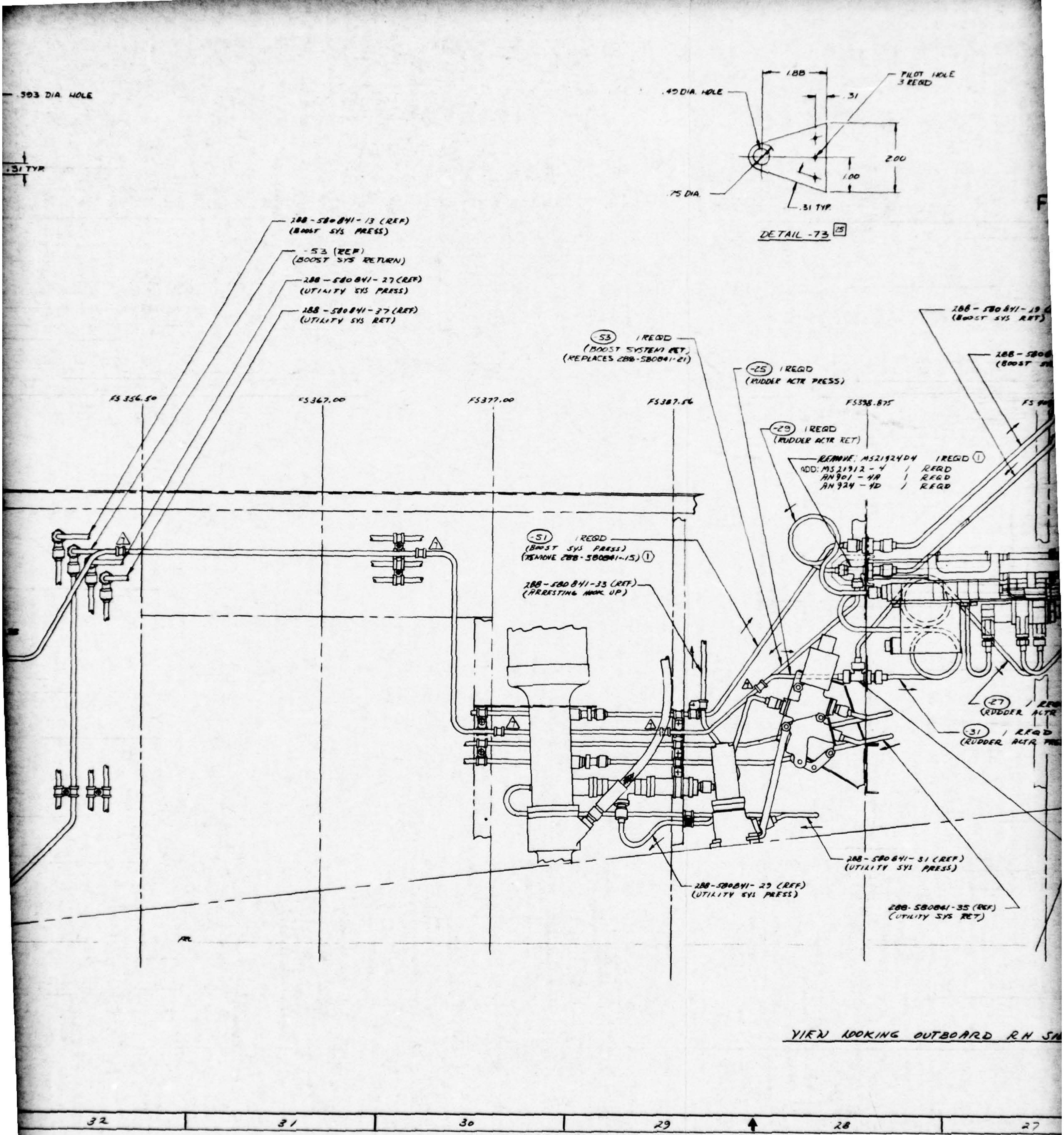

(-53) 1 REQD
(RUDDER SYS PRESS)
MS35207-261 2 REQD
MS21042L3 2 REQD
(PICK UP EXISTING HOLES IN SO 4266-01-13 BRACKET)
(-55) 1 REQD
(RUDDER SYS PRESS)
R44111T-04 1 REQD
R44359P-06 1 REQD
R44118T-06 1 REQD
AN901-6A 2 REQD
SO4266-02-010
(PUMP OUTPUT
288-580812-49 REF
(BOOST SYS PRESS)
288-580812-69 REF
(UTILITY SYS PRESS NO.2)
288-580812-29 (REF)
(UTILITY SYSTEM PRESS NO. 1)
R44598-6-0310 (REF)
(FOR CONTINUATION SEE ZONE 55
288-580812-63 (REF)
(UTILITY SYS PRESS NO. 2)
288-580812-21 (REF)
(UTILITY SYS. RET)
-37 REF
(FOR CONTINUATION)
SEE ZONE 56B
288-580812-67 (REF)
(UTILITY SYS PRESS NO. 1)
288-580811-79 (REF)
(UTILITY SYS PRESS)
3 REQD
MS24423-6
(-11) 1 REQD
(SUCTION)
-17 REF
(FOR CONTINUATION
SEE ZONE 57D)
WP - 4.50
1180 A 1 REQD
R44191P-0406 1 REQD
MS28778-6 6 REQD
MS21902-6 3 REQD
MS9058-06 1 REQD
AN6289-6 1 REQD
AN937D6 1 REQD
MS21924D6 1 REQD
ENLARGE EXISTING HOLE TO .781 DIA
MS21908-8 1 REQD
AN901-8A 2 REQD
AN924-8D 1 REQD
-21 (REF)
(FOR CONTINUATION
SEE ZONE 54F)
(-45) 1 REQD
MS21902-8 1 REQD
310-580811-39 (REF)
(LH BRAKE PRESS)
(-3) 1 REQD
(SUCTION)
-11 (REF)
PRESS)
288-580811-67 (REF)
(UTILITY SYS RET)
288-580812-39 (REF)
(UTILITY SYS PRESS)
211-35-000 1 REQD
R44182P-04 1 REQD
R44133T-04 1 REQD
MS28778-4 1 REQD
FS246.13
FS258.56
FS263.94
FS270.00
FS276.44
FS284.94
(-39) 1 REQD
(DRAIN)
SO 4266-03-012 1 REQD
(UTILITY SYS RET)
VIEW LKG OUTBD RH. SIDE
1 REQD
1 REQD
8691-580010
REV
SHEET 2
42
41
40
39
38

3



(-49) 1 REQD (RUDDER SYS PRESS)
(-13) 1 REQD (RUDDER SYS PRESS)
R44111T-04 1 REQD
-15 (REF)
-21 (REF)
DRILL F(.257) 2 HOLES
AC-1000-6NC 1 REQD
MS 2191606-4 1 REQD
AN893-2D 1 REQD
MS 24423-4 1 REQD
MS 28778-6 2 REQD
MS 28778-4 1 REQD
NAS 43DD4-40 2 REQD
AN4-26A 2 REQD
MS 21042L4 2 REQD
LD153-0002-1204 4 REQD
.75
-23 REF
12 13
58300 1 REQD (COOLER LH SIDE ONLY)
AN3-5A 4 REQD
LD153-0002-1203 8 REQD
MS 21042L3 4 REQD
R05-F-295 1 REQD
MS 35842-16 2 REQD
INSTALL PER DWG
SO 4266-01 SHT 2
2.50
.125
45° TYP
1.25
.69
.19 R.
.106
.31 TYP
DETAIL -75
(-15) 1 REQD (RUDDER SYS PRESS)
FS 300.00
FS 307.00
FS 312.75
FS 321.00
FS 329.00
FS 338.00
FS 347.00
FS 293.54
-47 REF (FOR CONTINUATION) SEE ZONE 22
288-580812-13 (REF) (UTILITY SYS PRESS)
REMOVE: 288-580812-17 1 REQD
ADD: SO 4266-03-011 1 REQD
(UTILITY SYS RET)
288-580819-3 (REF) (SPEED BRAKE OPEN)
.31
WP 20.28
249-31681-1 (REF)
2CK-L 1 REQD
B1/4 2 REQD
WP 17.06
249-31691-1 (REF)
WP 17.06
.38
249-31693-1 (REF)
HE271-0002-1012 (REF)
288-580841-7 (REF) (SPEED BRAKE CLOSE)
288-580841-9 (REF) (SPEED BRAKES CLOSE)
288-580841-11 (REF) (BOOST SYS PRESS)
288-580841-23 (REF) (BOOST SYS RET)
288-580841-25 (REF) (UTILITY SYS PRESS)
288-580841-3 (REF) (SPEED BRAKE OPEN)
288-580841-39 (REF) (UTILITY SYS RET)
288-580819-13 (REF) (UTILITY SYS RET)
288-580819-11 (REF) (UTILITY SYS PRESS)
288-580819-9 (REF) (BOOST SYS RET)
288-580819-7 (REF) (BOOST SYS PRESS)
288-580819-5 (REF) (SPEED BRAKE CLOSE)
8691-580010
REV
SHEET 2
37
36
35
34
33

4


.393 DIA. HOLE
.31 TYP
1.88
PILOT HOLE 3 REQD
.49 DIA. HOLE
.31
2.00
1.00
.75 DIA.
.31 TYP.
DETAIL -73 25
288-580841-13 (REF) (BOOST SYS PRESS)
-53 (REF) (BOOST SYS RETURN)
288-580841-27 (REF) (UTILITY SYS PRESS)
288-580841-37 (REF) (UTILITY SYS RET)
-53 1 REQD (BOOST SYSTEM RET) (REPLACES 288-580841-21)
-25 1 REQD (RUDDER ACTR PRESS)
-29 1 REQD (RUDDER ACTR RET)
REMOVE: MS21924D4 1 REQD 1
ADD: MS21912-4 1 REQD
AN901-4A 1 REQD
AN924-4D 1 REQD
288-580841-19 (BOOST SYS RET)
288-580 (BOOST
FS 356.50
FS 367.00
FS 377.00
FS 387.56
FS 398.875
-51 1 REQD (BOOST SYS PRESS) (REMOVE 288-580841-15) 1
288-580841-33 (REF) (ARRESTING HOOK UP)
-27 1 REQD (RUDDER ACTR
-31 1 REQD (RUDDER ACTR PRESS
288-580841-31 (REF) (UTILITY SYS PRESS)
288-580841-29 (REF) (UTILITY SYS PRESS)
288-580841-35 (REF) (UTILITY SYS RET)
VIEW LOOKING OUTBOARD RH SI
32
31
30
29
28
27
F

5

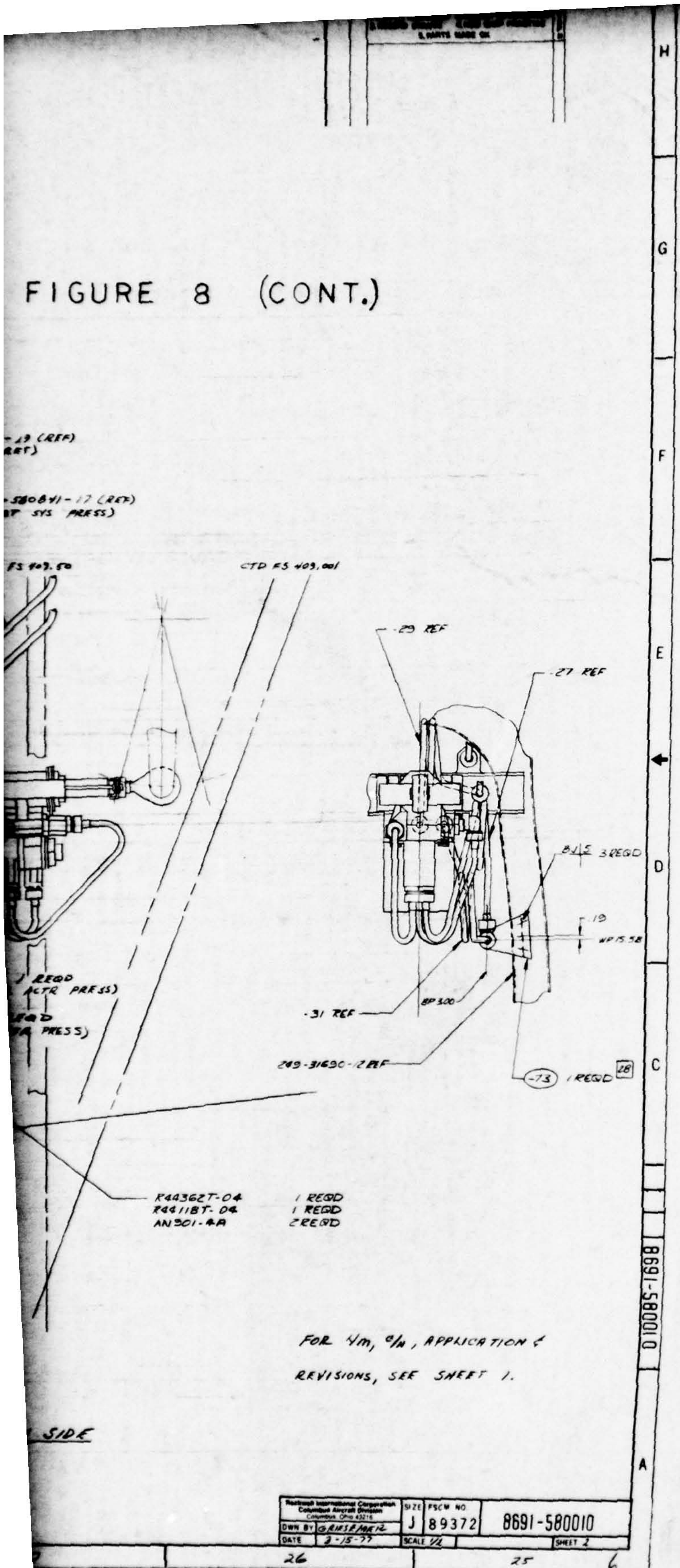


FIGURE 8 (CONT.)

A thermal analysis performed in Reference 4 indicated a heat exchanger would be required because of (1) the small surface area and volume of the 8000 psi system, and (2) the oversize 8000 psi pump. The 8000 psi pump had the potential for delivering 18.7 hp (13.9 kW). The output was reduced to 2.6 hp (1.9 kW) to match rudder actuator flow rates and T-2C electrical power generation capabilities.

Hydraulic fluid in the T-2C was changed from MIL-H-5606 to MIL-H-83282 for the LHS flight test program, Reference 13. This fluid was retained for the AFCAS program.

3.3.2 Motor/Pump Unit

Pump - The pump was designed and fabricated by the Aerospace Division of Abex Corporation in Oxnard, California, and was identified as M/N AP1V-106, P/N 63077. Design details are given in Reference 12. The pump is a constant pressure, variable displacement, axial piston unit, Figure 9. Rated delivery is 3.2 gpm (12.1 L/m) at 7330 rpm and 7850 psi (54 MPa) with a +180°F (82°C) inlet fluid temperature. Delivery was reduced for the AFCAS program to 0.54 gpm (2.04 L/m) at 8100 rpm and 7850 psi with a +180°F inlet fluid temperature.

Motor - The motor was designed and fabricated by the Aerospace Electrical Division of Westinghouse Electric Corporation, in Lima, Ohio. The unit was originally built to drive a New York Air Brake pump in a commercial airliner--the Lockheed "Jet Star". The motor has a radio noise filter, thermal protector, shock mounts, and is explosion-proof, Figure 9. The unit is rated for 8 hours continuous duty at 35,000 ft. (11 km); motor brushes have a design life of 500 hours. Rated output is 4.75 hp.

The motor, identified as P/N 914F591-2, had the following operating characteristics when coupled to Abex pump M/N AP1V-106:

Input voltage:	28 volts DC (nominal)
Running current:	140 amperes (after warm-up)
Starting current:	1000+ amperes for 0.035 sec. (1200 amperes peak)
Speed:	8100 rpm
Pump discharge pressure:	8000 psi (55 MPa)
Pump discharge flow:	250 cc/min

A view of the motor/pump installation is presented as Figure 10.

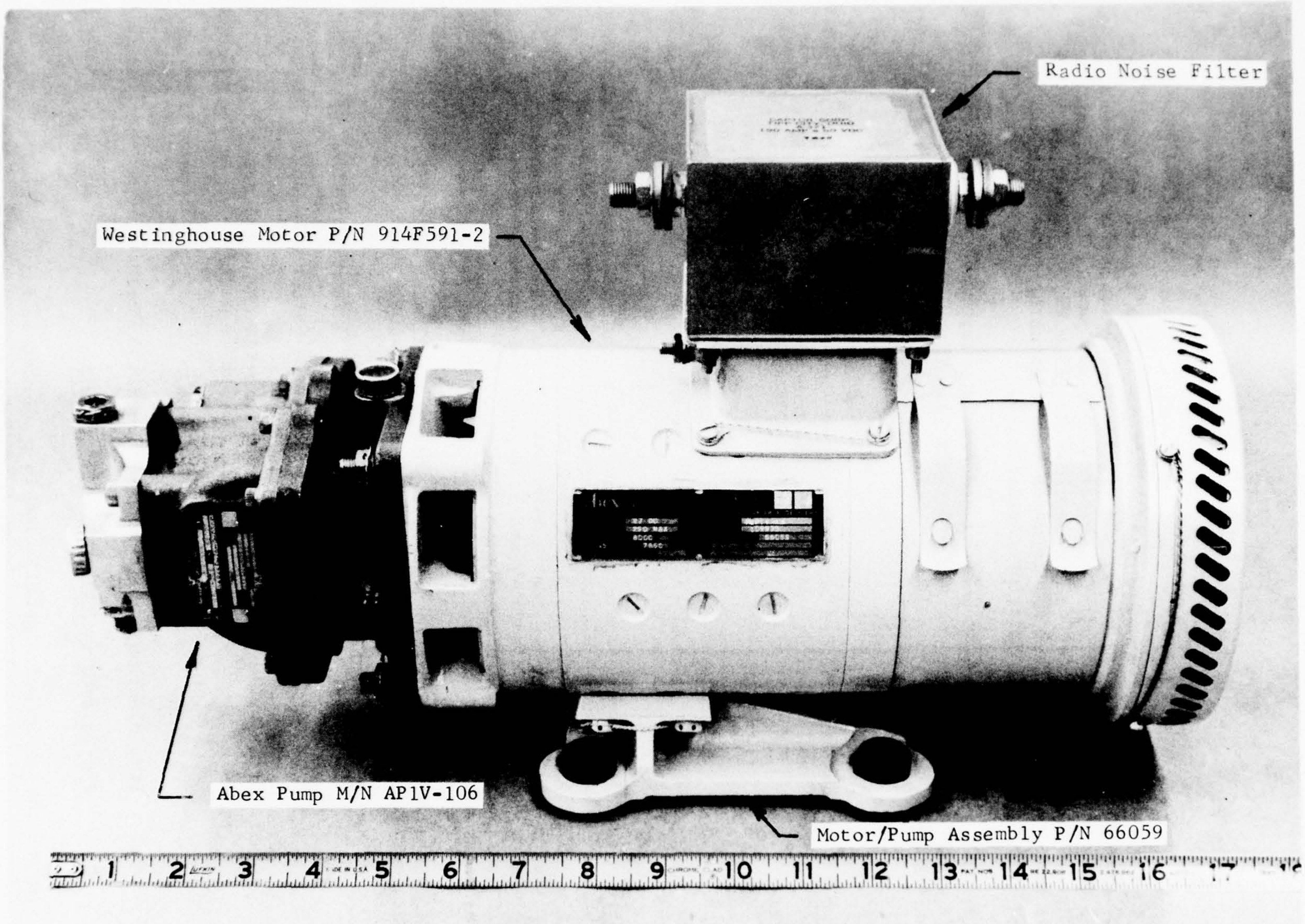


FIGURE 9 MOTOR/PUMP UNIT

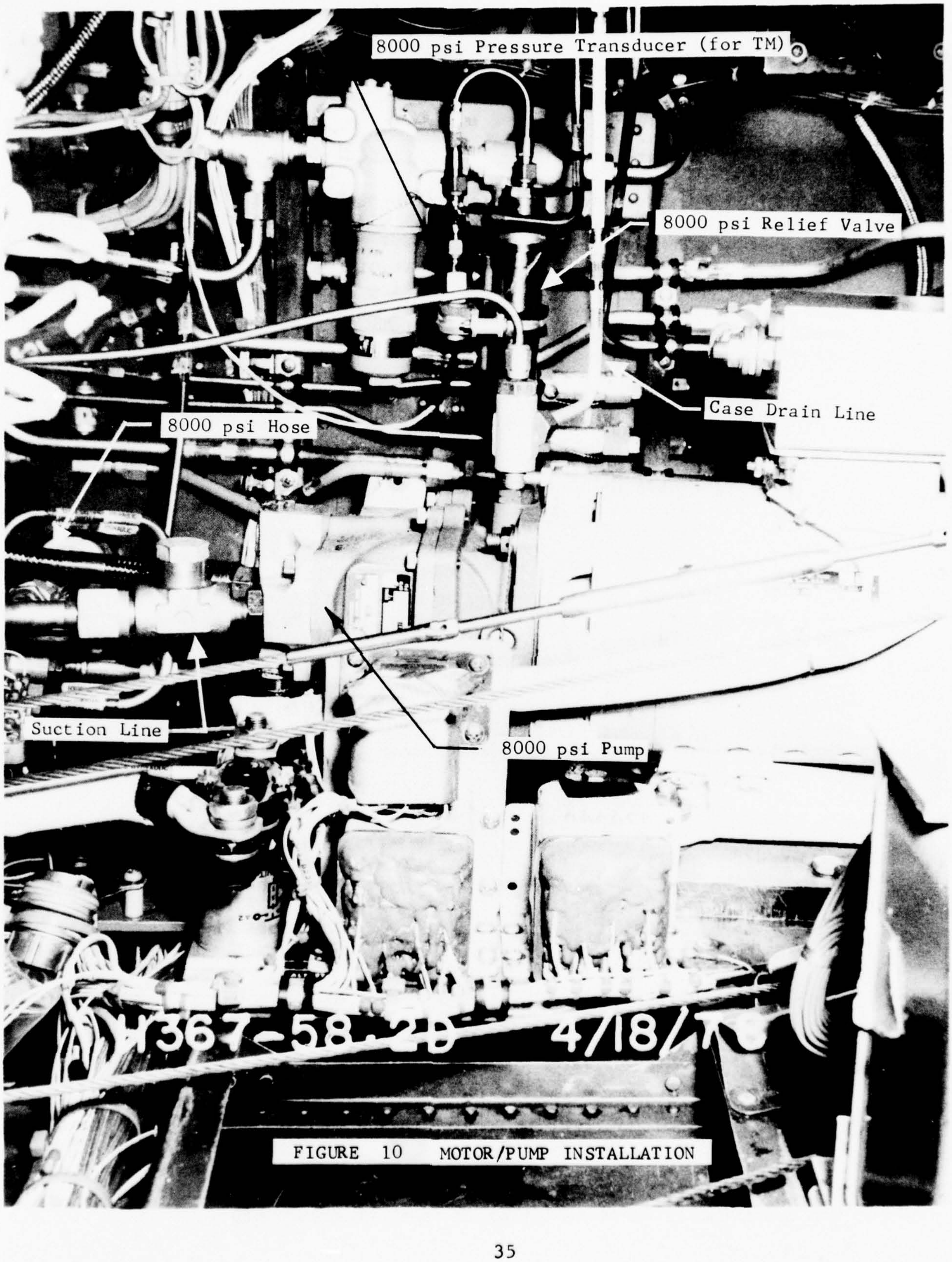


FIGURE 10 MOTOR/PUMP INSTALLATION

3.3.3 Rudder Actuator

The control-by-wire rudder actuator was designed by the Columbus Aircraft Division of Rockwell International under Contract N62269-75-C-0311, Reference 4. The assembly is an engineering model and should not be considered a final design. MIL-C-5503 requirements were followed except as modified for 8000 psi (55 MPa) operating pressure and utilization of some modularization techniques to achieve commonality. The actuator is shown on Figure 11. Design constants are listed below; design details are discussed in Reference 4.

Operating pressure	8000 psi (55 MPa)
Piston stroke (total)	3.5 in. (8.9 cm)
Cylinder bore	0.926 in. (2.3 cm)
Rod diameter	0.748 in. (1.9 cm)
Piston effective area	0.234 in^2 (1.5 cm^2)
Force output (max.)	1870 lb (8.3 kN)
Piston velocity (max.)	5.5 in/sec (14 cm/s)
Actuator length (extended)	18.375 in. (46.7 cm)

Actuator piston position and rate are commanded by a spool/sleeve type flow control valve. The valve spool is driven directly by a lever attached to the armature of a permanent magnet force (torque) motor mounted on the valve housing. The motor has four independent coils for redundancy. Actuator piston position feedback is provided by two DC-operated LVDT transducers, one mounted on each side of the unit. A by-pass valve was added to automatically interconnect the two cylinder chambers in the event hydraulic power were lost. Manufacturers of major components in the actuator were:

Part No.	Description	Manufacturer
8691-524001-101	Rudder Actuator Assembly	Columbus Aircraft Division of Rockwell International
8691-524001-051	Bypass Valve	Columbus Aircraft Division of Rockwell International
SO 4262-03-21	Control Valve	Ronson Hydraulic Units Corporation Charlotte, North Carolina
99-D0234 (M/N 21-6-200)	Force Motor	Servotronics, Inc. Buffalo, New York
2000 HCD	Position Transducer	Schaevitz Engineering Camden, New Jersey

The rudder actuator installation is shown on Figure 12.

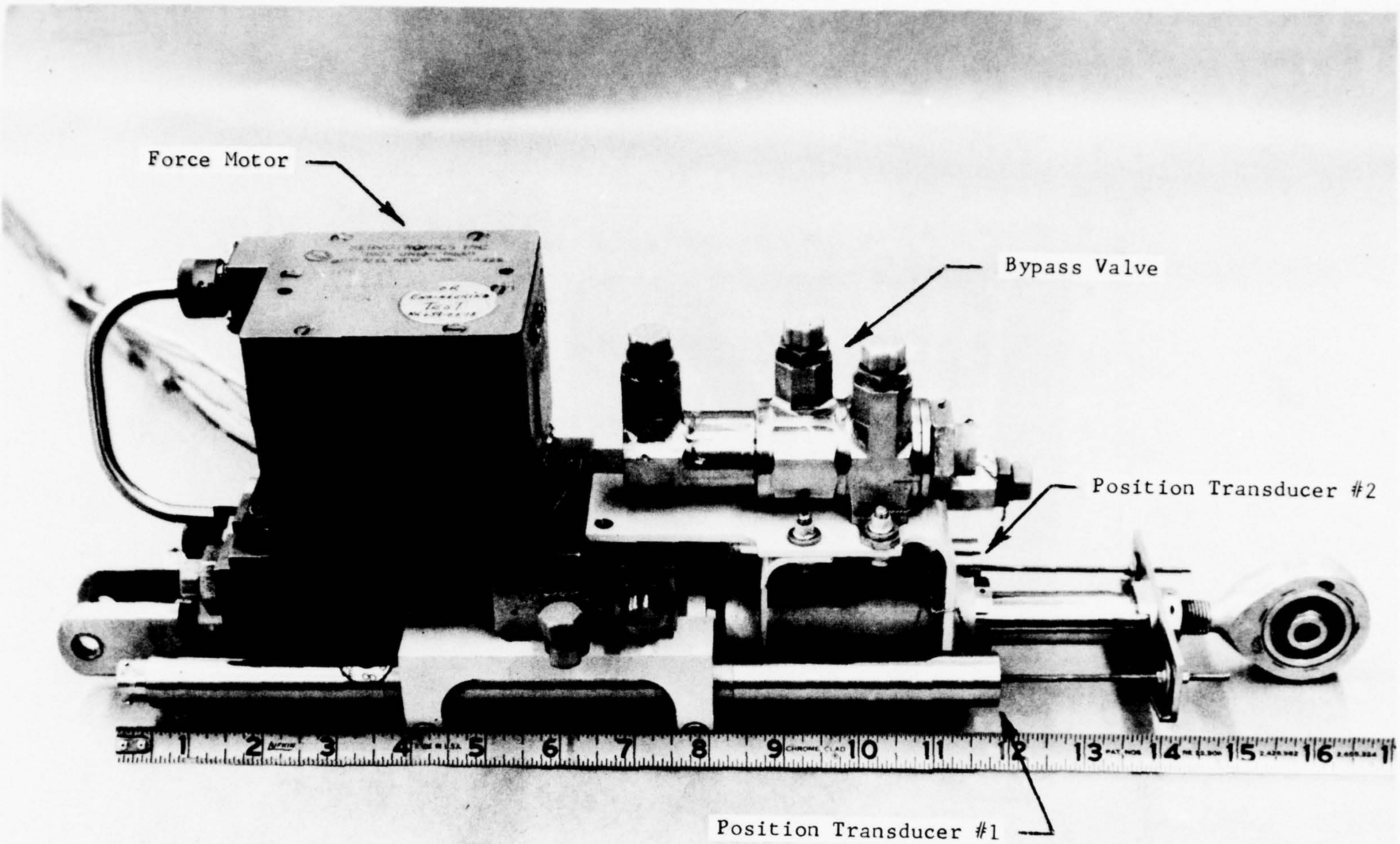


FIGURE 11   RUDDER ACTUATOR ASSEMBLY

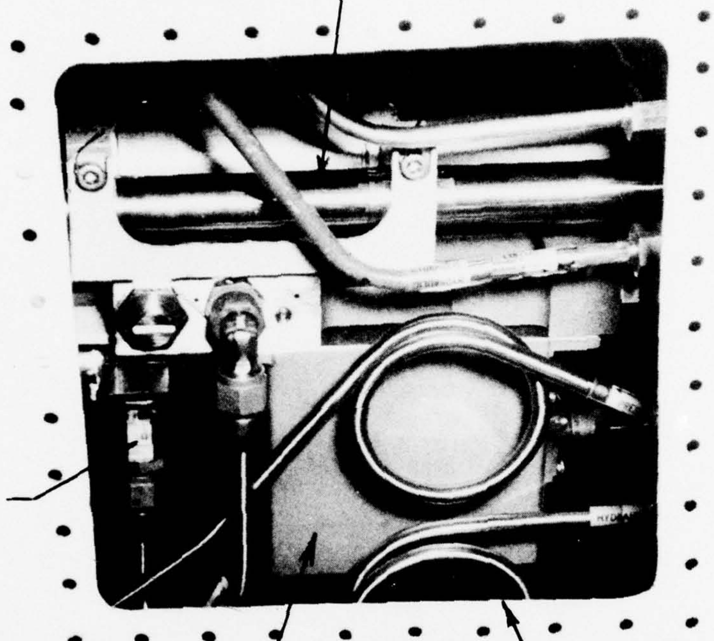


FIGURE 12 RUDDER ACTUATOR INSTALLATION

3.4 ELECTRICAL SYSTEM

3.4.1 Electronic Drive Unit (EDU)

The electronic drive unit, P/N 8691-546604, was designed and fabricated by the Columbus Aircraft Division of Rockwell International Corporation. Circuit concepts employed in the unit were developed under company funded IR&D projects. Innovative application of redundancy and feedback techniques permit EDU operation to be maintained with multiple component failures. Although the assembly was designed and fabricated to be suitable for flight, the EDU was nevertheless an experimental model. The assembly contained discrete components, test points, and external adjustments to facilitate data acquisition. This resulted in a much larger package than would be needed for a production unit. A production design EDU would have approximately 5% of the volume of the AFCAS unit.

The EDU was powered by 115 volt 400 ~ AC and basically had two channels with dual sub-circuits (4 channels total). Bias pots were provided to adjust the input, feedback, and balance of each channel. Two power supplies provided ±15 VDC for the signal amplifiers and system transducers. All circuitry was contained on two identical printed circuit boards, Figure 15.

3.4.2 Force Transducer

The force transducer housing assembly, P/N 8691-524001-61, was designed and fabricated by CAD, Figure 14. The housing contains two DC-operated LVDT force transducers, P/N FTD-1T-500, built by Schaevitz Engineering in Camden, New Jersey. The units have a maximum capacity of 500 lb (2.2 kN), a spring rate of approximately 8000 lb/in (1.40 MN/m), and an output of 0.01 v/lb (.002 v/N) in tension or compression.

3.4.3 AFCAS Circuitry

A simplified block diagram of all elements in the system is shown on Figure 16. Pilot inputs are transmitted through the rudder pedals via cables, pulleys, and bellcranks to the force transducer located inside the vertical stabilizer. Gearing multiplies pilot effort by 2.28. Transducer output is the command signal (e_i) to the EDU. Amplifiers in the EDU process e_i with a feedback signal (e_{fb}) and power the force motor coils which drive the spool X_i in the control valve. The valve ports 8000 psi hydraulic fluid to the rudder actuator in response to X_i. Actuator piston travel is sensed by position transducers having an output of 5 v/in; this is the feedback signal (e_{fb}). Actuator piston travel (±1.75 in. max.) is converted through a bellcrank and push rod to angular travel of the rudder (±12° max.).

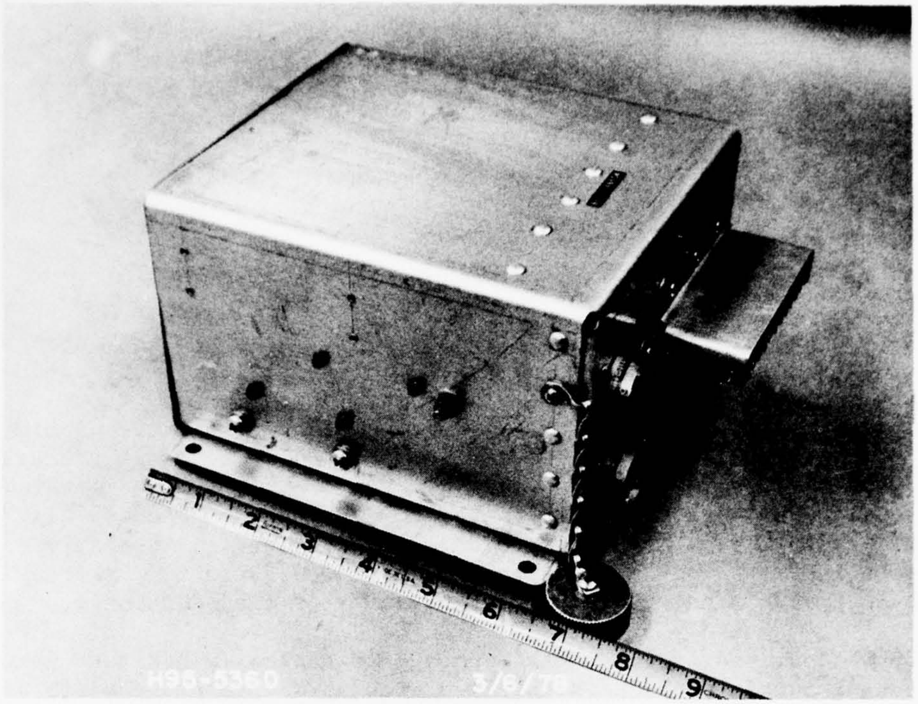


FIGURE 13 ELECTRONIC DRIVE UNIT

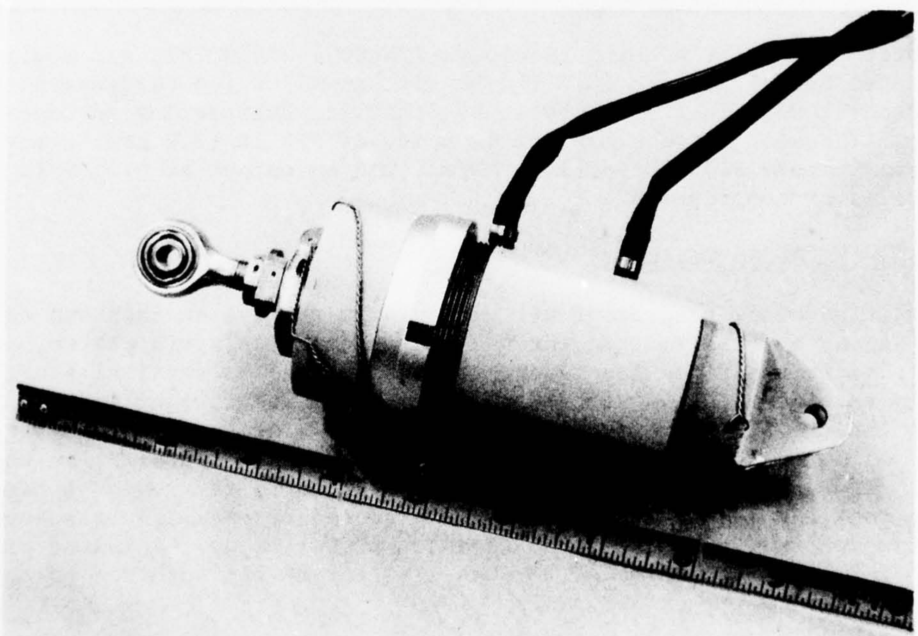


FIGURE 14 FORCE TRANSDUCER

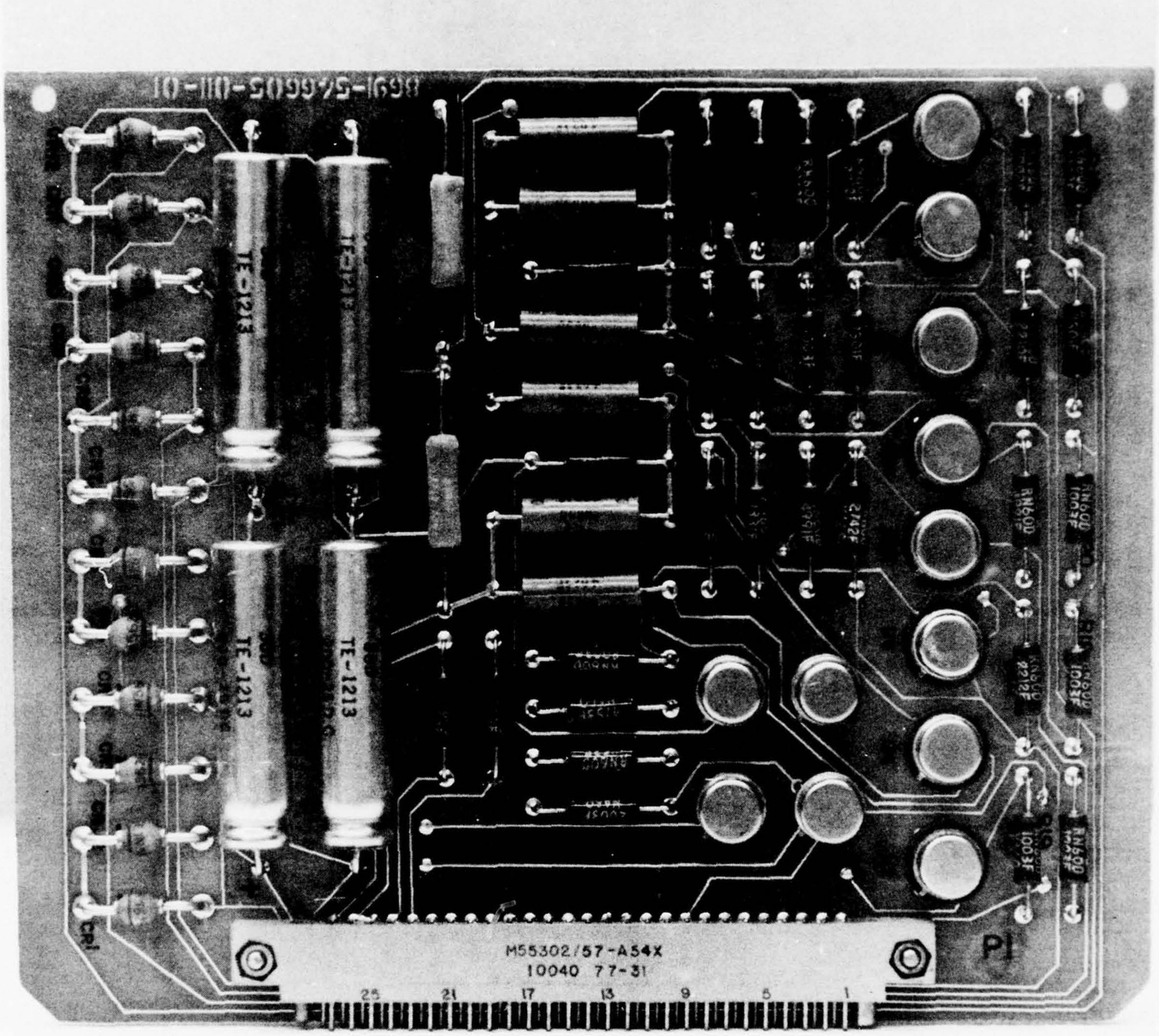


FIGURE 15 EDU PRINTED CIRCUIT BOARD

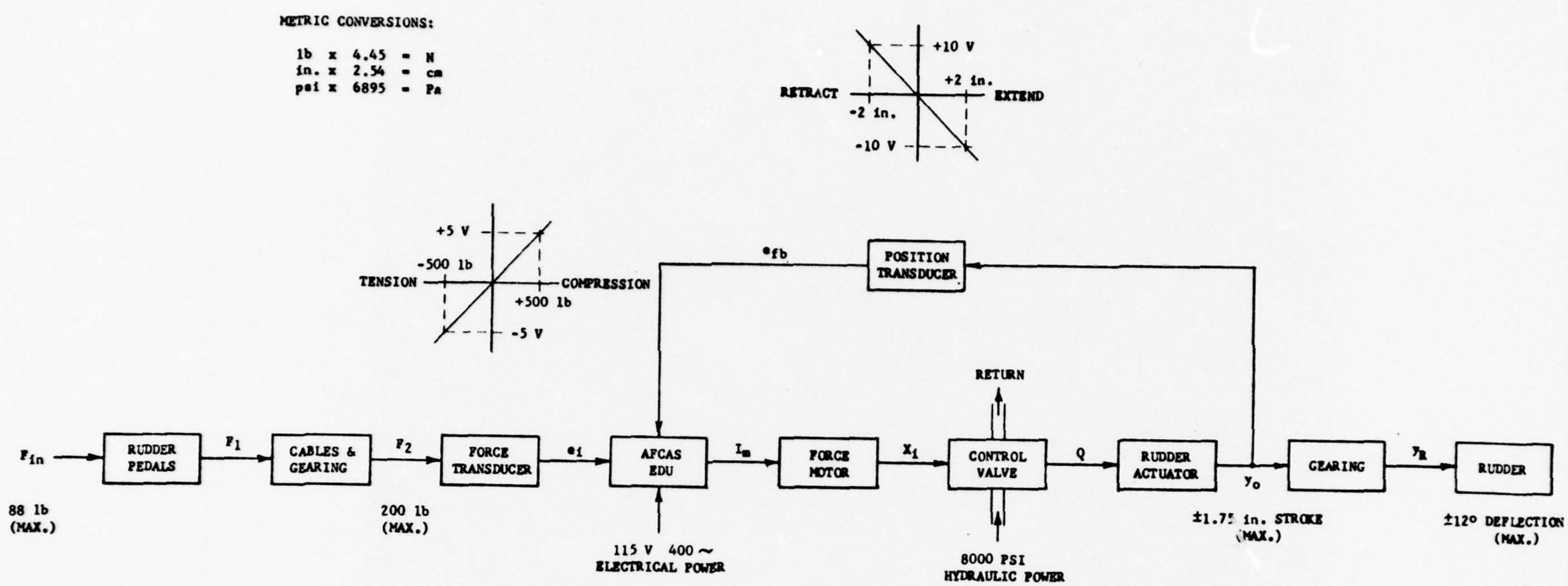


FIGURE 16 BLOCK DIAGRAM OF SYSTEM

A simplified diagram of electrical components in the test installation is presented on Figure 17. System redundancy is illustrated on Figure 18. The system concept developed under CAD IR&D studies is flexible in that various levels of redundancy could be employed (as required) for other applications. AFCAS redundancy features include:

- Dual force (input) transducers
- Dual position (feedback) transducers
- Dual power supplies
- Quad electronics
- Feedback fault correction

A schematic diagram of EDU electronics is presented on Figure 20. The diagram also shows test points and adjustment features added for the AFCAS program. Each of the four power amplifiers employs current feedback with a highly reliable darlington power transistor configuration and independent power supplies. The circuitry is designed so that in the event an output stage fails "hard-over", voltage applied to a motor coil will not exceed its rated value. This limiting feature permits a subunit failure to be compensated or nullified by another subunit. Closed loop tests reported in Reference 3 verified that operation of the redundant subunits provided high immunity to component failures.

A math model of the idealized system is presented on Figure 19. The transfer functions are for "small signal" inputs and do not reflect fluid flow saturation limitations or motor current limitations imposed by coil inductance. System spring-mass effects (actuator loaded) were not included. Optimum loop gain was 90; this provided a theoretical band width of 14.3 Hz and a damping ratio of 0.7.

Performance characteristics of the test installation were higher than could be utilized in the T-2C rudder system. To assure satisfactory operation, AFCAS dynamics were matched with T-2C directional system dynamics. This was accomplished by lowering loop gain to 20 and adding high frequency roll-off filtering to reduce the possibility of system noise.

3.4.4 AFCAS Installation

The wiring diagram detailing AFCAS interconnecting cables and terminals is presented as Figure 21. Standard plugs and shielded wiring were used throughout the system. AC and DC power control relays, circuit breakers, and cockpit wiring are detailed on Figure 22. The electronic drive unit was installed on the forward bulkhead of the T-2C fuselage compartment, Figure 23.

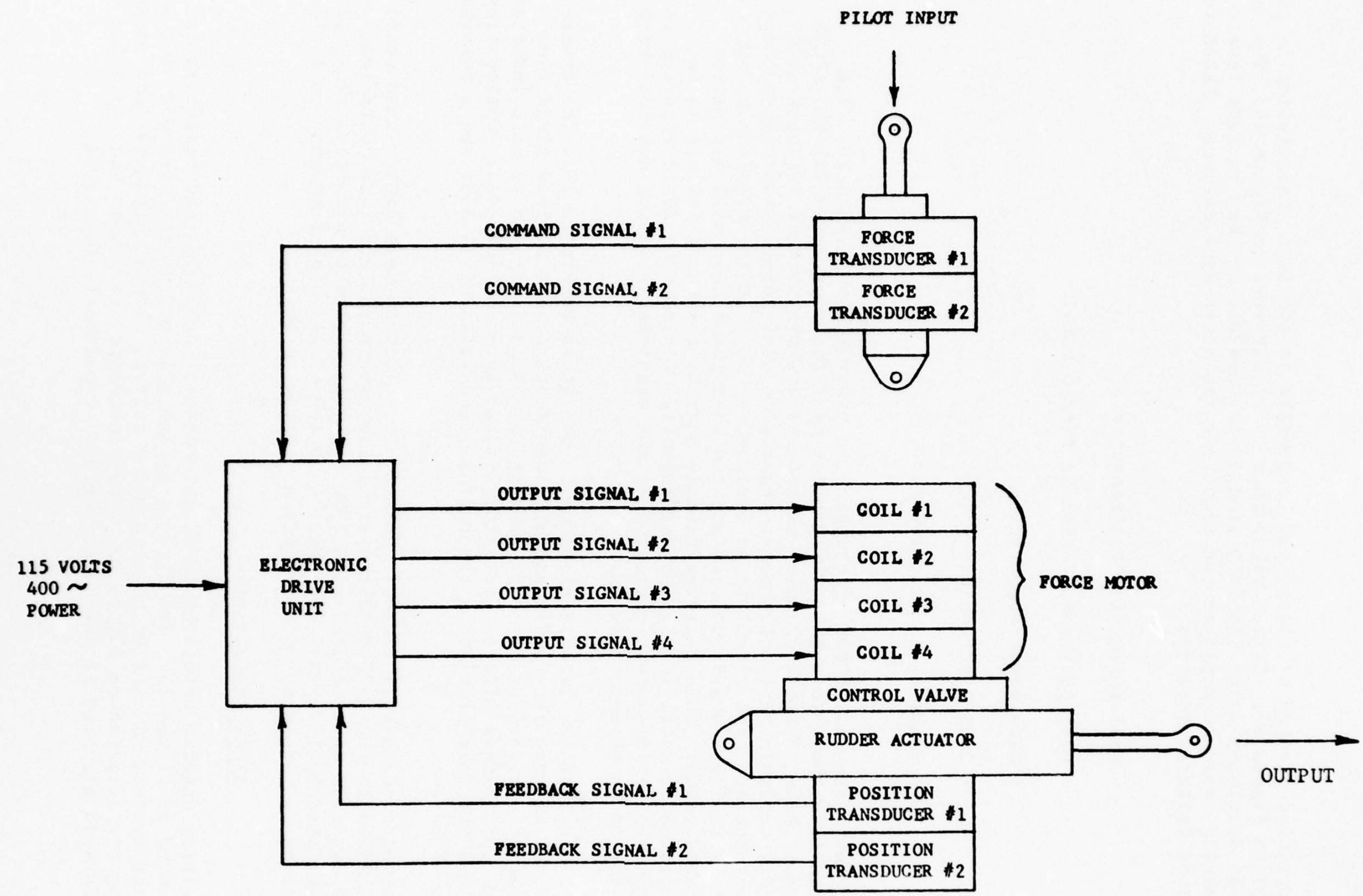
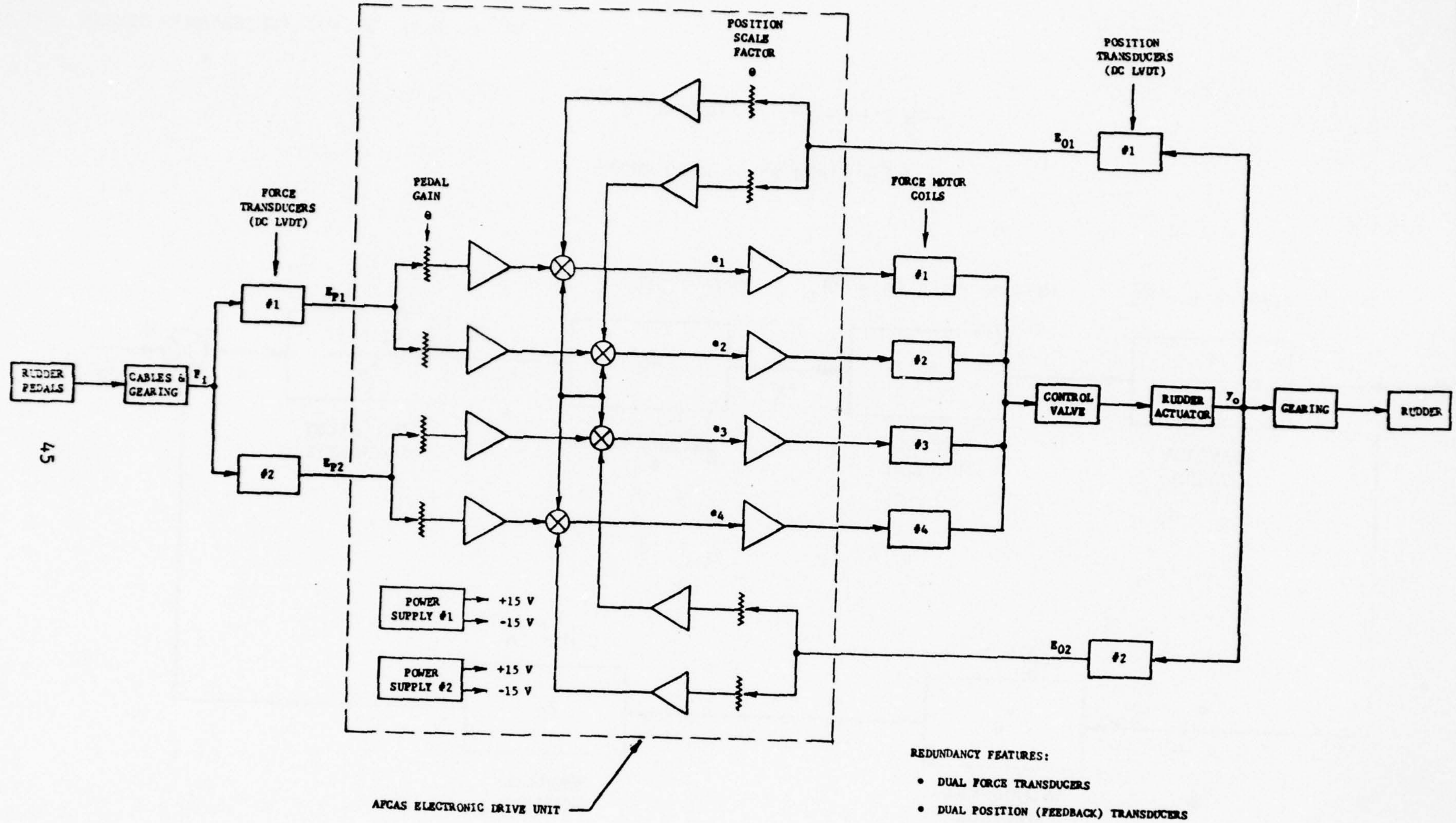


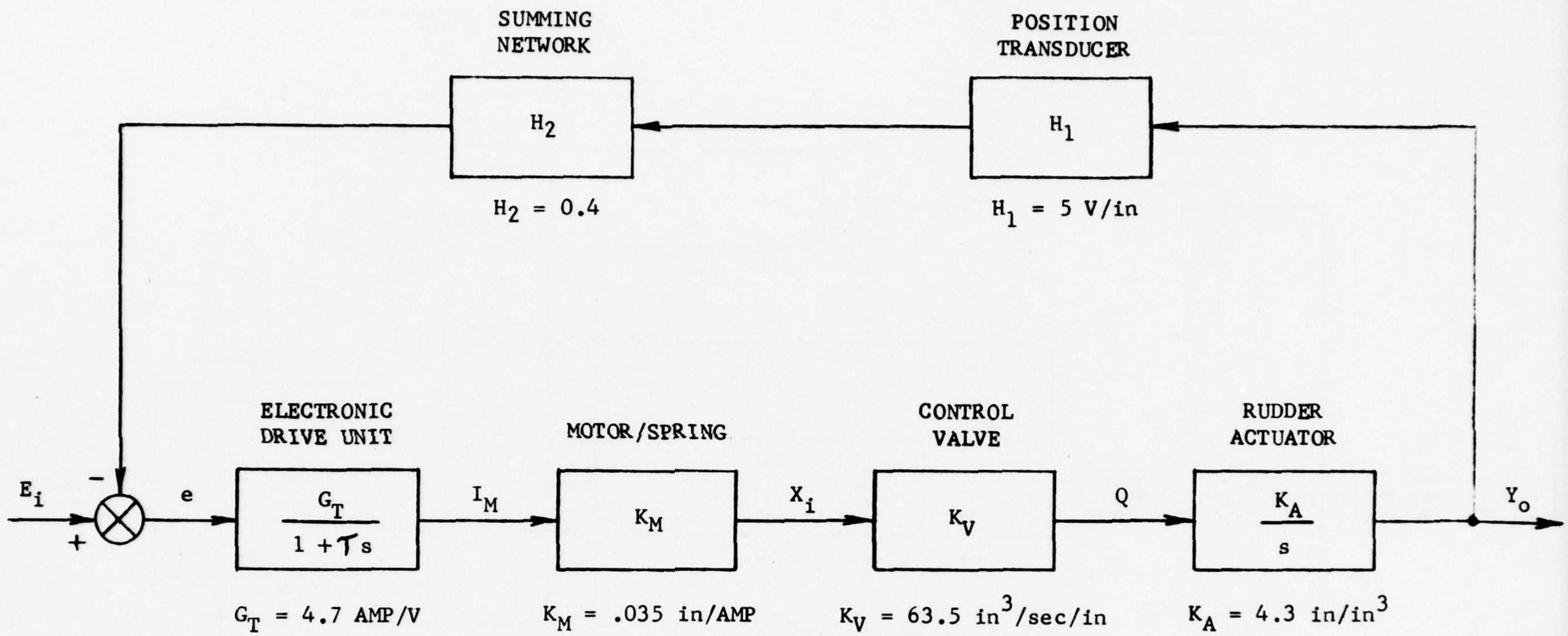
FIGURE 17 SIMPLIFIED DIAGRAM OF ELECTRICAL COMPONENTS



REDUNDANCY FEATURES:

- DUAL FORCE TRANSDUCERS
- DUAL POSITION (FEEDBACK) TRANSDUCERS
- QUAD ELECTRONICS
- EXPANDED COMMON POINT CONTROL
- DUAL POWER SUPPLIES

FIGURE 18 SIMPLIFIED DIAGRAM SHOWING SYSTEM REDUNDANCY

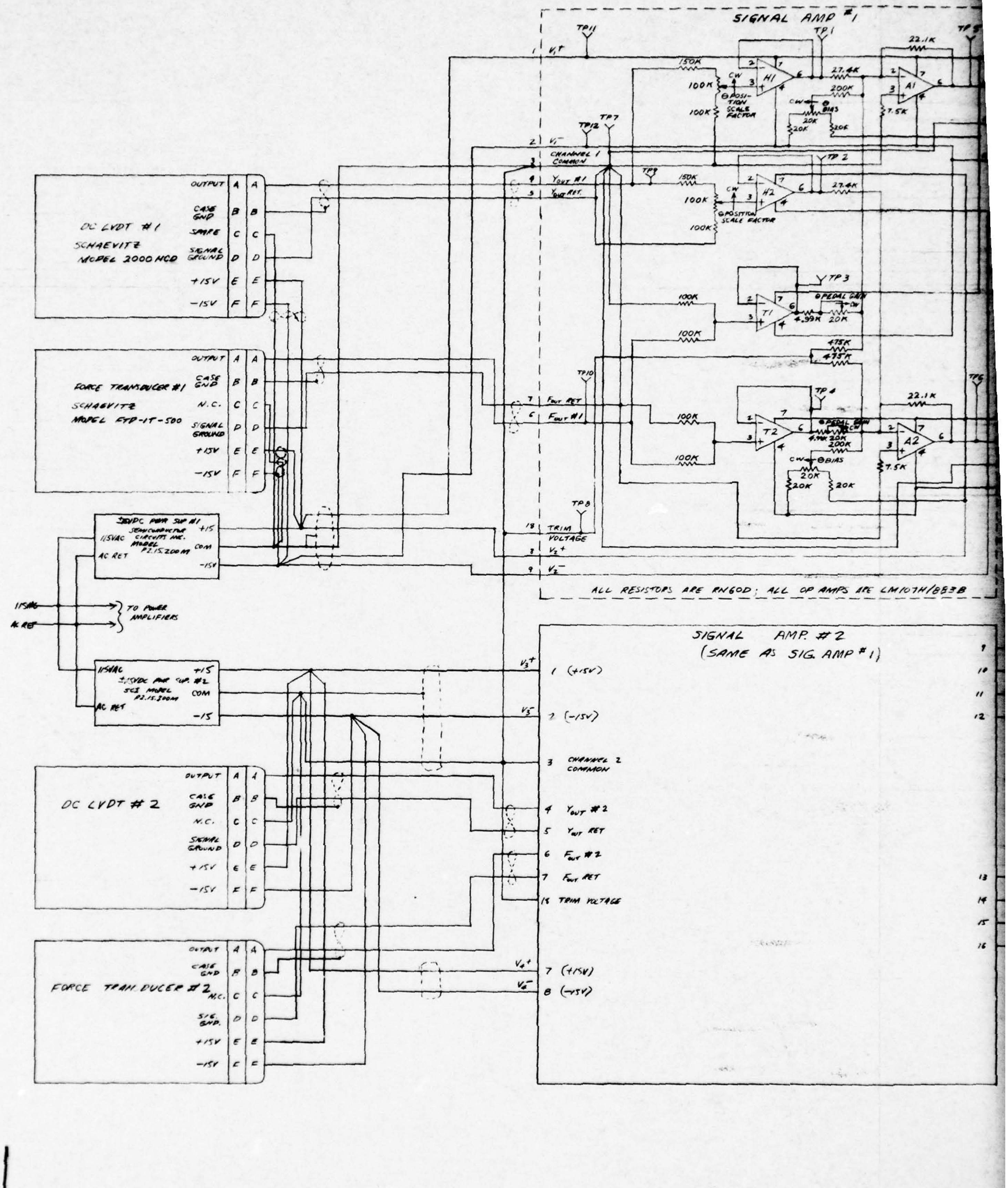


$$\text{LOOP GAIN} = G_T K_M K_V K_A H_1 H_2 = 90$$

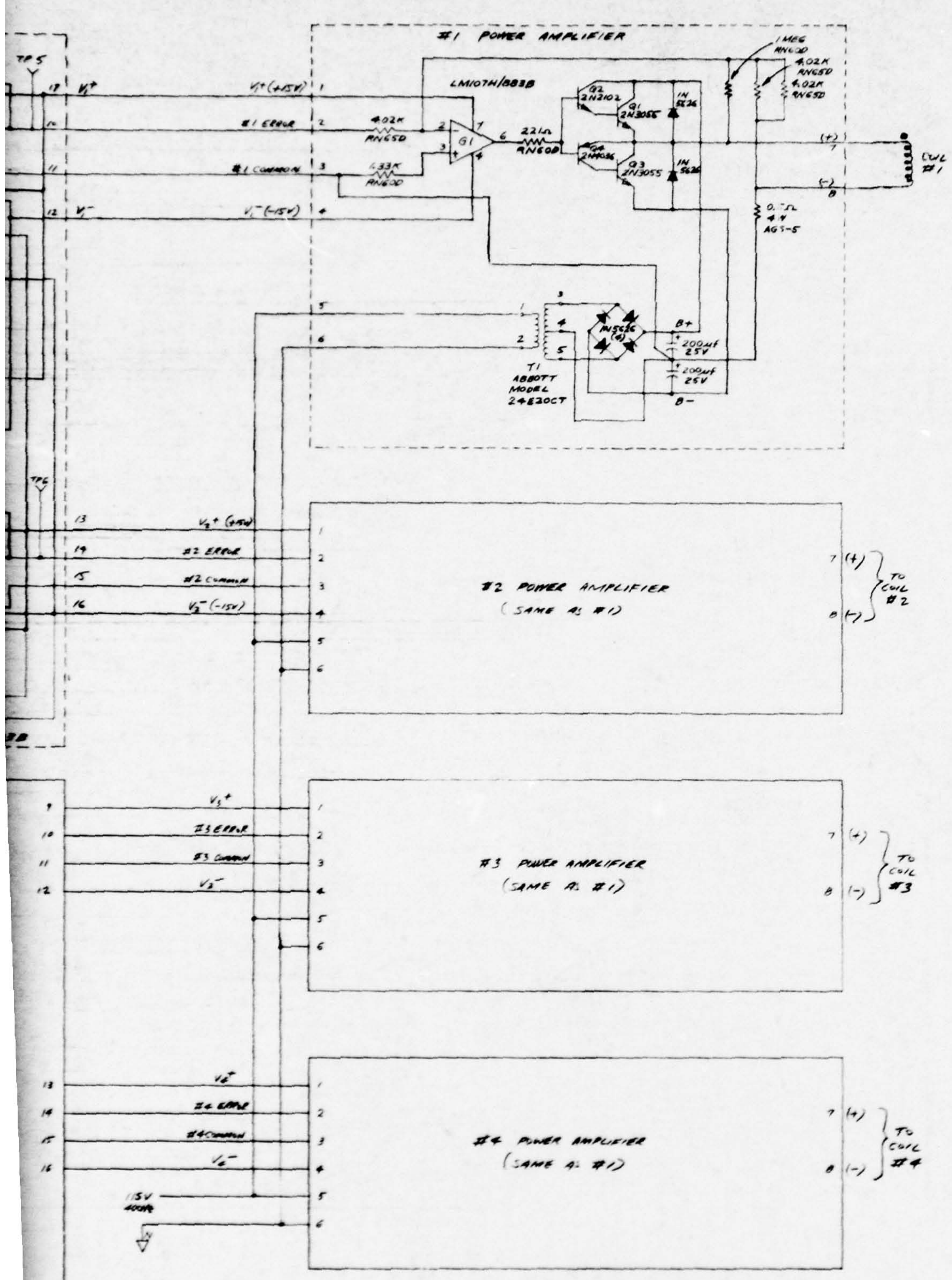
$$\text{BAND WIDTH} = \frac{90}{2\pi} = 14.3 \text{ Hz}$$

METRIC CONVERSION: in X 2.54 = cm

FIGURE 19 MATH MODEL

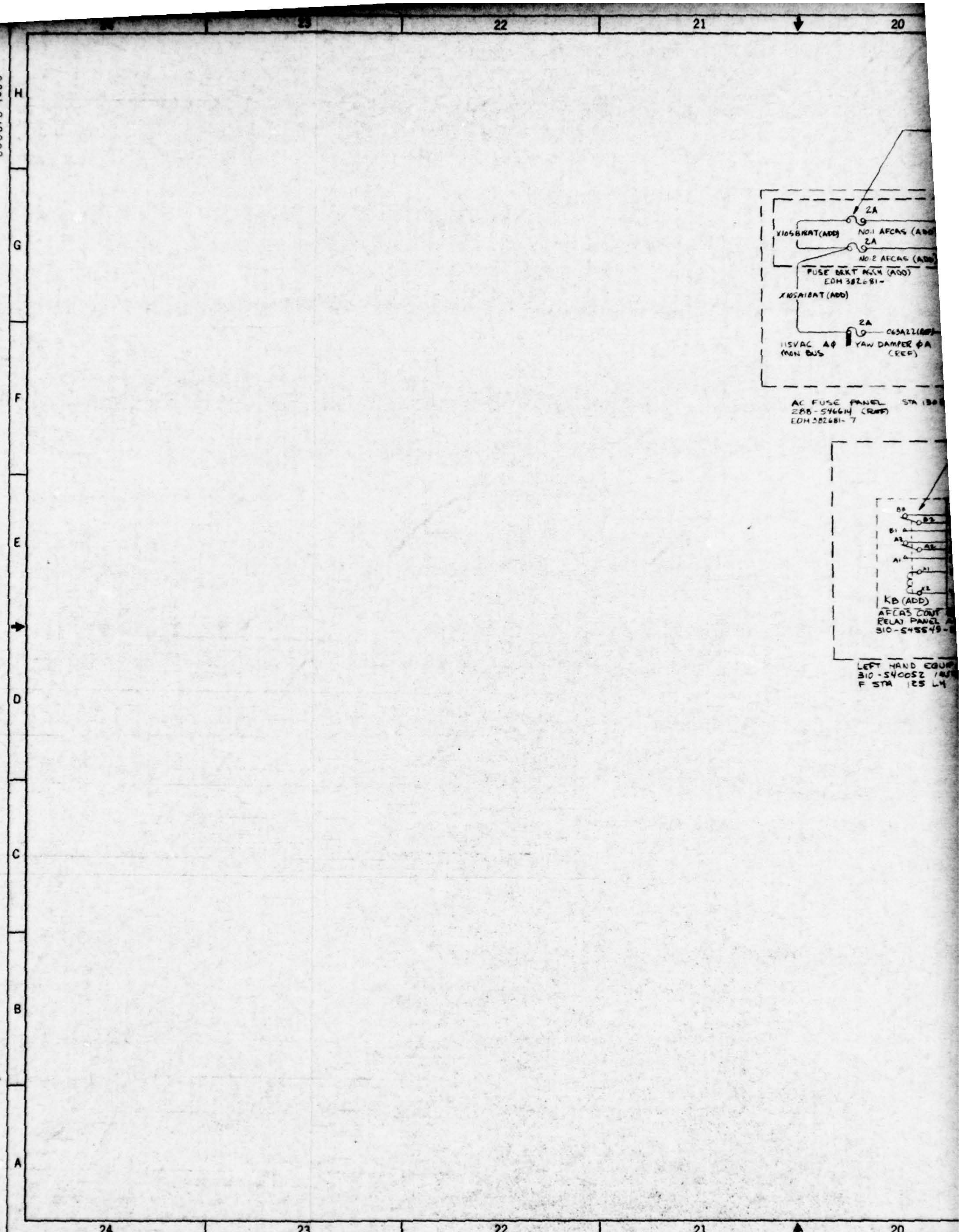


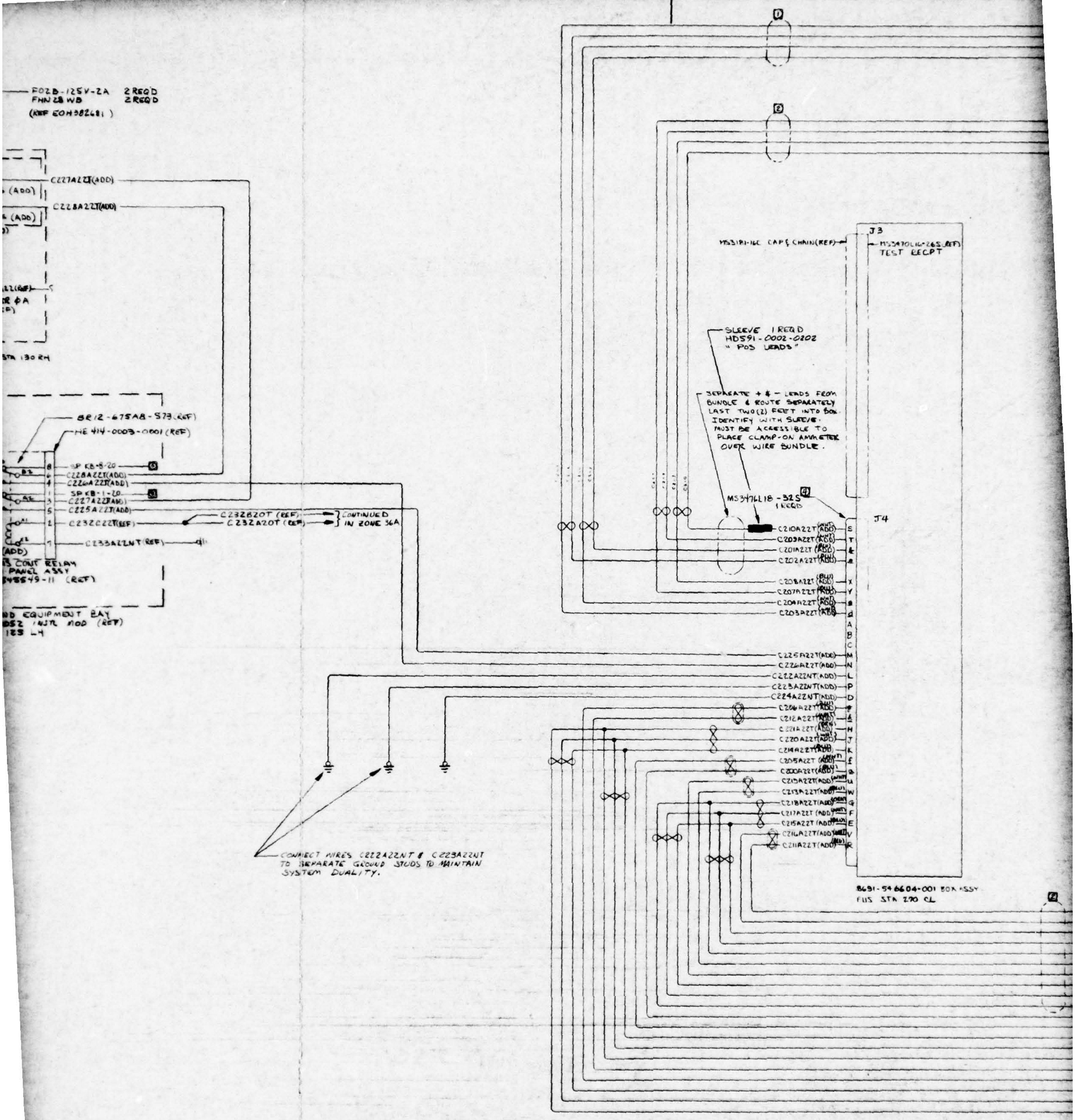
SIGNAL AMP #1
DC LVDT #1
SCHAEVITZ
MODEL 2000 HCD
OUTPUT
CASE GND
SPARE
SIGNAL GROUND
+15V
-15V
FORCE TRANSDUCER #1
SCHAEVITZ
MODEL FTD-1T-500
N.C.
±15VDC PWR SUP #1
SEMICONDUCTOR CIRCUITS INC.
MODEL P2.15.200M
115VAC
AC RET
COM
115VAC
AC RET
TO POWER AMPLIFIERS
CHANNEL 1 COMMON
TRIM VOLTAGE
POSITION SCALE FACTOR
PEDAL GAIN
BIAS
ALL RESISTORS ARE RN60D; ALL OP AMPS ARE LM107H/883B
SIGNAL AMP. #2
(SAME AS SIG. AMP #1)
±15VDC PWR SUP. #2
SCS MODEL P2.15.200M
1 (+15V)
2 (-15V)
3 CHANNEL 2 COMMON
4 YOUT #2
5 YOUT RET
6 FOUT #2
7 FOUT RET
18 TRIM VOLTAGE
7 (+15V)
8 (-15V)
DC LVDT #2
FORCE TRANSDUCER #2
SIG. GND.



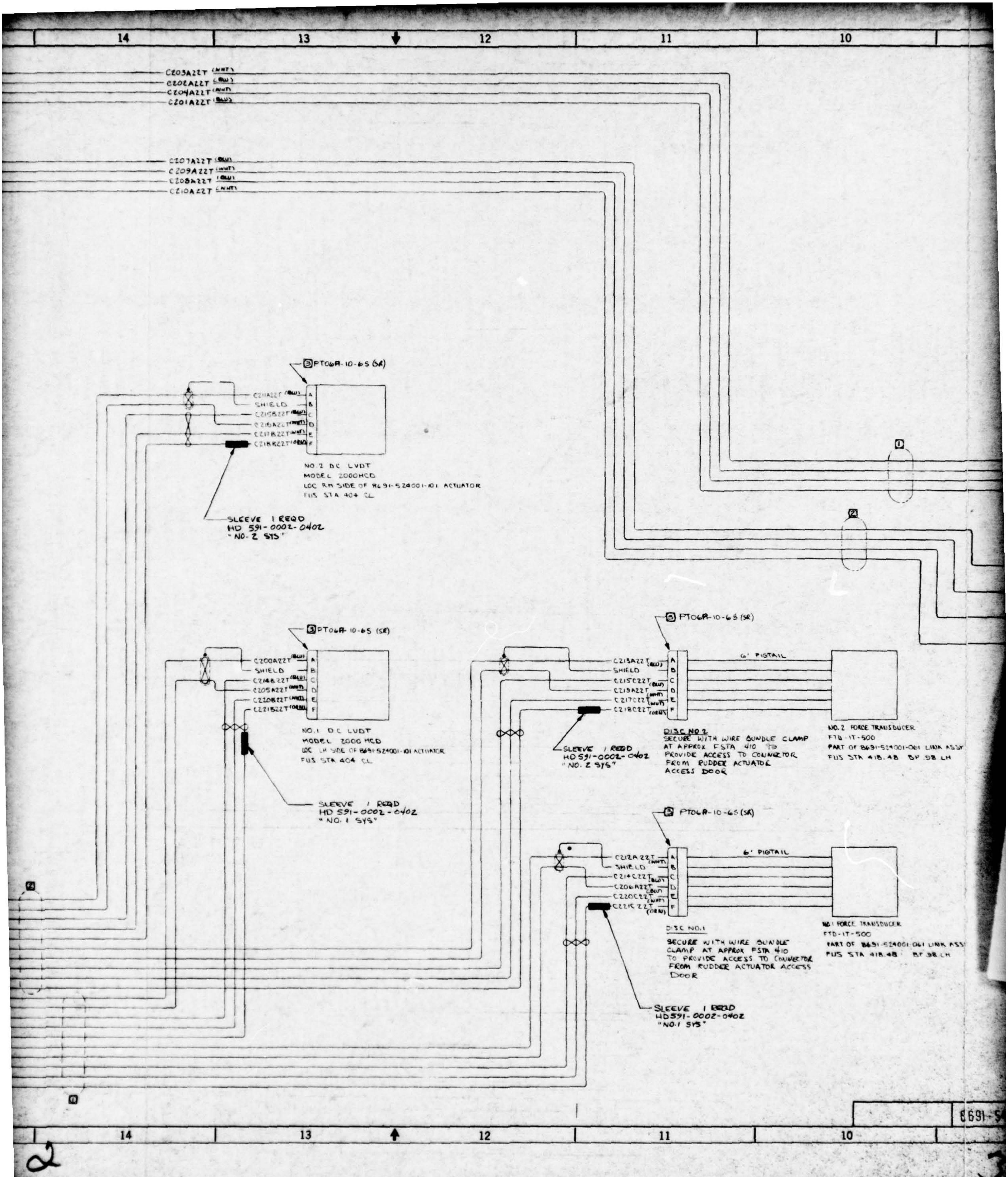
SCHEMATIC DIAGRAM
T-2 AFCAS ELECTRONICS
B. MATHENA 12-7-76
REV 3-1-77
REV 3-3-77
REV. 3-22-77
5-10-77 CHANGED 470K TO 475K

FIGURE 20


24
23
22
21
20
H
G
F
E
D
C
B
A
2A
X105BKAT(ADD)
NO.1 AFCAS
2A
NO.2 AFCAS
FUSE BRKT ASSY (ADD)
EDH 382681-
X105A1BAT(ADD)
2A
115VAC AΦ
MON BUS
YAW DAMPER ΦA
(REF)
AC FUSE PANEL
288-546614 (REF)
EDH 382681- 7
B1
A1
KB (ADD)
AFCAS CONT
RELAY PANEL
LEFT HAND EQUIP
F STA 125 LH



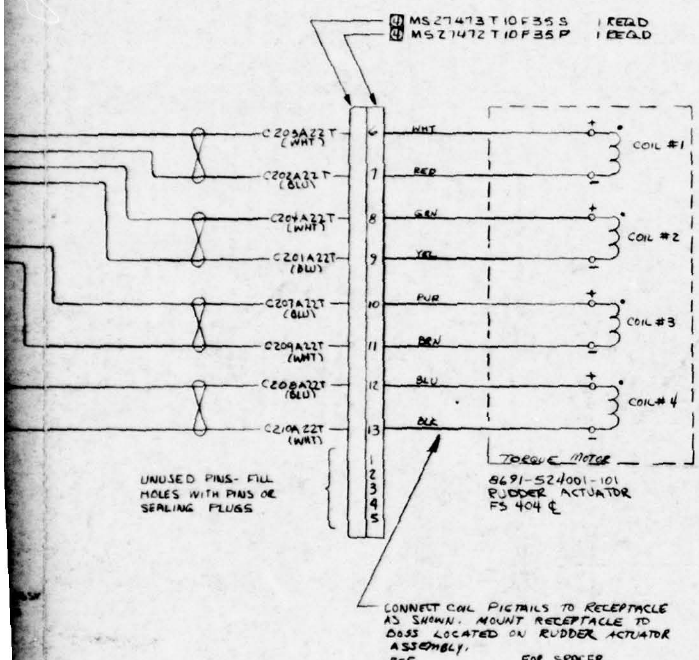
	8691-546606	REV	SHEET 1



14
13
12
11
10
C203A22T (WHT)
C202A22T (BLU)
C204A22T (WHT)
C201A22T (BLU)
C207A22T (BLU)
C209A22T (WHT)
C208A22T (BLU)
C210A22T (WHT)
5 PT06A-10-6S (SR)
C211A22T (BLU) A
SHIELD B
C215B22T (BLU) C
C216A22T (WHT) D
C217B22T (WHT) E
C218B22T (ORN) F
NO.2 DC LVDT
MODEL 2000HCD
LOC RH SIDE OF 8691-524001-101 ACTUATOR
FUS STA 404 CL
SLEEVE 1 REQD
HD 591-0002-0402
"NO. 2 SYS"
1
2
5 PT06A-10-6S (SR)
C200A22T (BLU) A
SHIELD B
C214B22T (BLU) C
C205A22T (WHT) D
C220B22T (WHT) E
C221B22T (ORN) F
NO.1 DC LVDT
MODEL 2000HCD
LOC LH SIDE OF 8691-524001-101 ACTUATOR
FUS STA 404 CL
SLEEVE 1 REQD
HD 591-0002-0402
"NO. 1 SYS"
5 PT06A-10-6S (SR)
C213A22T (BLU) A
SHIELD B
C215C22T (BLU) C
C213A22T (WHT) D
C217C22T (WHT) E
C218C22T (ORN) F
6' PIGTAIL
DISC NO 2
SECURE WITH WIRE BUNDLE CLAMP AT APPROX FSTA 410 TO PROVIDE ACCESS TO CONNECTOR FROM RUDDER ACTUATOR ACCESS DOOR
NO.2 FORCE TRANSDUCER
FTD-1T-500
PART OF 8691-524001-061 LINK ASSY
FUS STA 418.48 BP 98 LH
SLEEVE 1 REQD
HD 591-0002-0402
"NO. 2 SYS"
5 PT06A-10-6S (SR)
C212A22T (WHT) A
SHIELD B
C214C22T (BLU) C
C206A22T (BLU) D
C220C22T (WHT) E
C221C22T (ORN) F
6' PIGTAIL
DISC NO.1
SECURE WITH WIRE BUNDLE CLAMP AT APPROX FSTA 410 TO PROVIDE ACCESS TO CONNECTOR FROM RUDDER ACTUATOR ACCESS DOOR
NO.1 FORCE TRANSDUCER
FTD-1T-500
PART OF 8691-524001-061 LINK ASSY
FUS STA 418.48 BP 98 LH
SLEEVE 1 REQD
HD591-0002-0402
"NO.1 SYS"
4
3
8691-5
14
13
12
11
10

2

3



WIRE NUMBER	TYPE	TERMINAL	TERMINAL	COLOR
X105B18AT	M22759/16-18-9	M7928/1-31	M7928/1-31	–
X105A18AT	M22759/16-18-9	M7928/1-31	M7928/1-31	–
P900A0T	MS90294-01-9	HE416-0008-0003	HE416-0008-0003	–
C241A0NT	MS90294-01-9	YAN1001/0 STR-L	YAN1001/0 STR-L	–
C240A0T	MS90294-01-9	YAN1001/0 STR-L	YAN1001/0 STR-L	–
C239A0T	MS90294-01-9	YAN1001/0 STR-L	HE416-0008-0003	–
C238A22T	M22759/16-22-9	—	M7928/1-15	–
C237A20NT	M22759/16-20-9	M7928/1-24	M7928/1-23	–
C235A20T	M22759/16-20-9	—	—	–
C234A20T		—	ST4110206HE0001	–
C233A22NT		M7928/1-15	—	–
C232C22T		ST4110206HE0001(REF)	—	–
C232B20T		ST4110206HE0001(REF)	M7928/1-23	–
C232A20T	M22759/16-20-9	ST4110206HE0001	—	–
C228A22T	M22759/16-22-9	M7928/1-13	—	–
C227A22T		M7928/1-13	—	–
C226A22T		—	—	–
C225A22T		—	—	–
C224A22NT		—	M7928/1-15	–
C223A22NT		—	M7928/1-15	–
C222A22NT	M22759/16-22-9	—	M7928/1-15	–
C221C22T	M7078/16-22-3	—	ST4110206HE0001(REF)	ORN
C221B22T	M7078/16-22-3	—	ST4110206HE0001(REF)	ORN
C221A22T	M7078/16-22-3	—	ST4110206HE0001	ORN
C220C22T	M7078/16-22-3	ST4110206HE0001(REF)	—	WHT
C220B22T	M7078/16-22-3	ST4110206HE0001(REF)	—	WHT
C220A22T	M7078/16-22-3	ST4110206HE0001	—	WHT
C219A22T	M7078/26-22-2	—	—	WHT
C218C22T	M7078/16-22-3	—	ST4110206HE0001(REF)	ORN
C218B22T	M7078/16-22-3	—	ST4110206HE0001(REF)	ORN
C218A22T	M7078/16-22-3	—	ST4110206HE0001	ORN
C217C22T	M7078/16-22-3	ST4110206HE0001(REF)	—	WHT
C217B22T	M7078/16-22-3	ST4110206HE0001(REF)	—	WHT
C217A22T	M7078/16-22-3	ST4110206HE0001	—	WHT
C216A22T	M7078/26-22-2	—	—	WHT
C215C22T	M7078/16-22-3	ST4110206HE0001(REF)	—	BLU
C215B22T	M7078/16-22-3	ST4110206HE0001(REF)	—	BLU
C215A22T	M7078/16-22-3	ST4110206HE0001	—	BLU
C214C22T	M7078/16-22-3	ST4110206HE0001(REF)	—	BLU
C214B22T	M7078/16-22-3	ST4110206HE0001(REF)	—	BLU
C214A22T	M7078/16-22-3	ST4110206HE0001	—	BLU
C213A22T	M7078/26-22-2	—	—	BLU
C212A22T	M7078/26-22-2	—	—	WHT
C211A22T	M7078/26-22-2	—	—	BLU
C210A22T	M7078/16-22-2	—	—	WHT
C209A22T	M7078/16-22-2	—	—	WHT
C208A22T	M7078/16-22-2	—	—	BLU
C207A22T	M7078/16-22-2	—	—	BLU
C206A22T	M7078/26-22-2	—	—	BLU
C205A22T	M7078/26-22-2	—	—	WHT
C204A22T	M7078/16-22-2	—	—	WHT
C203A22T	M7078/16-22-2	—	—	WHT
C202A22T	M7078/16-22-2	—	—	BLU
C201A22T	M7078/16-22-2	—	—	BLU
C200A22T	M7078/26-22-2	—	—	BLU

ADD WIRE LIST

WIRE NUMBER	TERMINAL	TERMINAL
C4F18		
C3F18		
D5A22-T	—	MS25274-
D4A22-T	—	M7928/1-

RECONNECT WIRE LIST

9 9. TO BE USED ON T-2C SHIP 1, BUNO152382 FOR TEST PER G.O. 8691.
8 8. INSTRUMENTATION WIRING. REF EOH377038.
5 7. SYMBOL DENOTES MS25274 WIRE END CAP TO BE USED ON SPARE WIRE.
3 6. MATING CONNECTOR SUPPLIED WITH EQUIPMENT ITEM.
2 5. SYMBOL DENOTES SYS NO.2 WIRES. BUNDLE & ROUTE SEPARATE FROM SYS NO.1 WIRES.
1 4. SYMBOL DENOTES SYS NO.1 WIRES. BUNDLE & ROUTE SEPARATE FROM SYS NO.2 WIRES.
3. REF THE FOLLOWING DWGS & EO'S FOR LOCATION OF COMPONENTS:
8691-546603 ELECTRICAL INSTALLATION
8691-580010 HYDRAULIC INSTATION
8691-524001 RUDDER INSTALLATION
EOH 382481
4 2. PART FURNISHED BY CAD ENGINEERING DEPT 71-542
1. SEE DWG. 288-540002 FOR FABRICATION & SPECIFICATIONS
NOTES UNLESS OTHERWISE NOTED

BSC	1	
ITEM	QTY	NEXT
REQD PER END ITEM		

691-546606 REV SHEET 1

9 8 7 6 5 4

3 4

4	3	2	1	12

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED
		1. MAY BE REWORKED 2. CANNOT BE REWORKED 3. RECORD CHANGE 4. NOW SHOP PRACTICE 5. PARTS MADE OK		

FIGURE 21

	ITEM OR FIND NO	QUANTITY REQUIRED	CODE IDENT	PART OR IDENTIFYING NUMBER	NOMENCLATURE	MATERIAL	THKNS GAUGE	WIDTH OD/ID	LG	DRAWING OR SPECIFICATION NUMBER	ZONE
		4		M7928/1-31	TERMINAL					MIL-T-7928	
		1		M7928/1-24	TERMINAL						
		2		M7928/1-23	TERMINAL						
		5		M7928/1-15	TERMINAL						
	043	3		M7928/1-13	TERMINAL					MIL-T-7928	
	042	2		LD153-0011-0017	AL WASHER						
	041										
	040										
4	039	5	07922	YAN1001/0 STRL	TERMINAL						
	038										
	037	8		ST4110206HE0001	SPLICE					VENDOR ITEM SEE SOURCE CONT DWG	
	036										
4	035	1	91929	6ET4-T	SWITCH					NAS-75655	
	034										
	033	2	81349	F02B-125V-2A	FUSE					MIL-F-15160D	
	032	2	81349	FHN28WB	FUSEHOLDER					MIL-F-19207/17	
	031										
4	030	1	09026	BR12-675AB-573	RELAY					NAS-73642	
4	029	3		HE416-0008-0003	TERM RT ANG					VENDOR ITEM SEE SOURCE CONT DWG	
4	028	1		HE414-0003-0001	CONN - RELAY					VENDOR ITEM SEE SOURCE CONT DWG	
	027										
	026	2		HD591-0002-0402	ID SLEEVE - "NO. 2 SYS"	MAKE FROM					
	025	2		HD591-0002-0402	ID SLEEVE - "NO. 1 SYS"	MAKE FROM					
	024	1		HD591-0002-0202	ID SLEEVE - "POS LEADS"	MAKE FROM					
	023										
	022										
3	021	4		PT06A10-6S(SR)	CONN PLUG						
4	020	1	96906	MS39064-2	CIRCUIT BREAKER - 200A						
4	019	1	96906	MS3476L18-32S	CONN PLUG						
	018										
	017	AR	96906	M22759/16-18-9	WIRE					MIL-W-22759	
	016	3	96906	MS25274-2	TIPIT						
4	015	1	96906	MS24171D1	RELAY						
4	014	1	96906	MS27473T10F35S	CONN PLUG						
4	013	1	96906	MS27472T10F35P	CONN RECPT						
	012	AR	96906	M22759/16-20-9	WIRE					MIL-W-22759	
	011	AR	96906	M22759/16-22-9	WIRE					MIL-W-22759	
	010	AR	96906	M7078/16-22-2	WIRE	2 COND TW				MIL-C-7078	
	009	AR	96906	M7078/16-22-3	WIRE	3 COND TW				MIL-C-7078	
	008	AR	96906	M7078/26-22-2	WIRE	2 COND TW SHLD				MIL-C-7078	
	007	AR	96906	MS90294-01-9	WIRE					MIL-W-22759/4	
	006	1	96906	MS35338-46	LOCK WASHER						
	005	1	96906	MS21042-6	NUT						
	004	1	96906	AN961-616T	WASHER						
	003	1	96906	AN6-13A	BOLT						
	002										
	001			8691-546606	WIRING DIAGRAM						

BSC

PARTS LIST

MS25274-2
M7928/1-13
TERMINAL
LIST

QTY	NEXT ASSY	USED ON	END ITEM NO	THRU
1	4	8691	TEST	
APPLICATION		EFFECTIVITY		

HEAT TREAT

FINISH

INSPECT PER MIL-I-6870 (ST0501LF0007 CLASS)

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. MFG TOLERANCES ON:
UNDIMENSIONED ±.03
XX (DECIMALS) ±.03
XXX (DECIMALS) ±.010
ANGLES ±30'
HOLES NOTED "DRILL"
.013 THRU .040 +.001 -.001
.041 THRU .130 +.002 -.001
.131 THRU .229 +.003 -.001
.230 THRU .500 +.004 -.001
.501 THRU .750 +.005 -.001
.751 THRU 1.000 +.007 -.001
1.001 THRU 2.000 +.010 -.001
DO NOT SCALE PRINT

CONTR NO.		
DWN BY	M. TAYLOR	2-25-77
CHK BY	P.J. Sermon	1/3/78
APVD		

Columbus Division
North American Rockwell
COLUMBUS, OHIO 43216

WIRING DIAGRAM- ADVANCED FLIGHT CONTROL ACTUATION SYSTEM

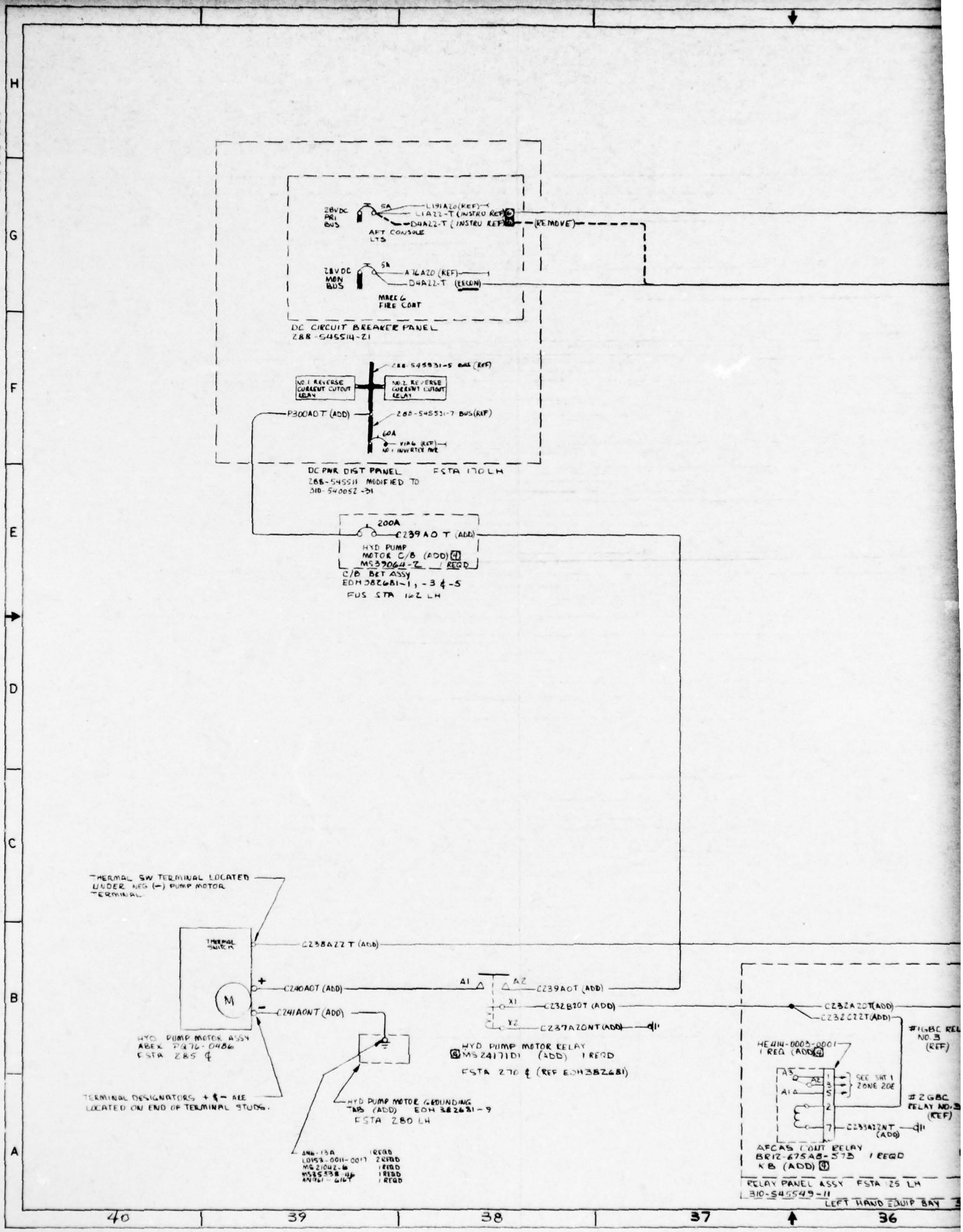
SIZE	CODE IDENT NO.	
J	89372	8691-546606
SCALE		SHEET

8691-546606

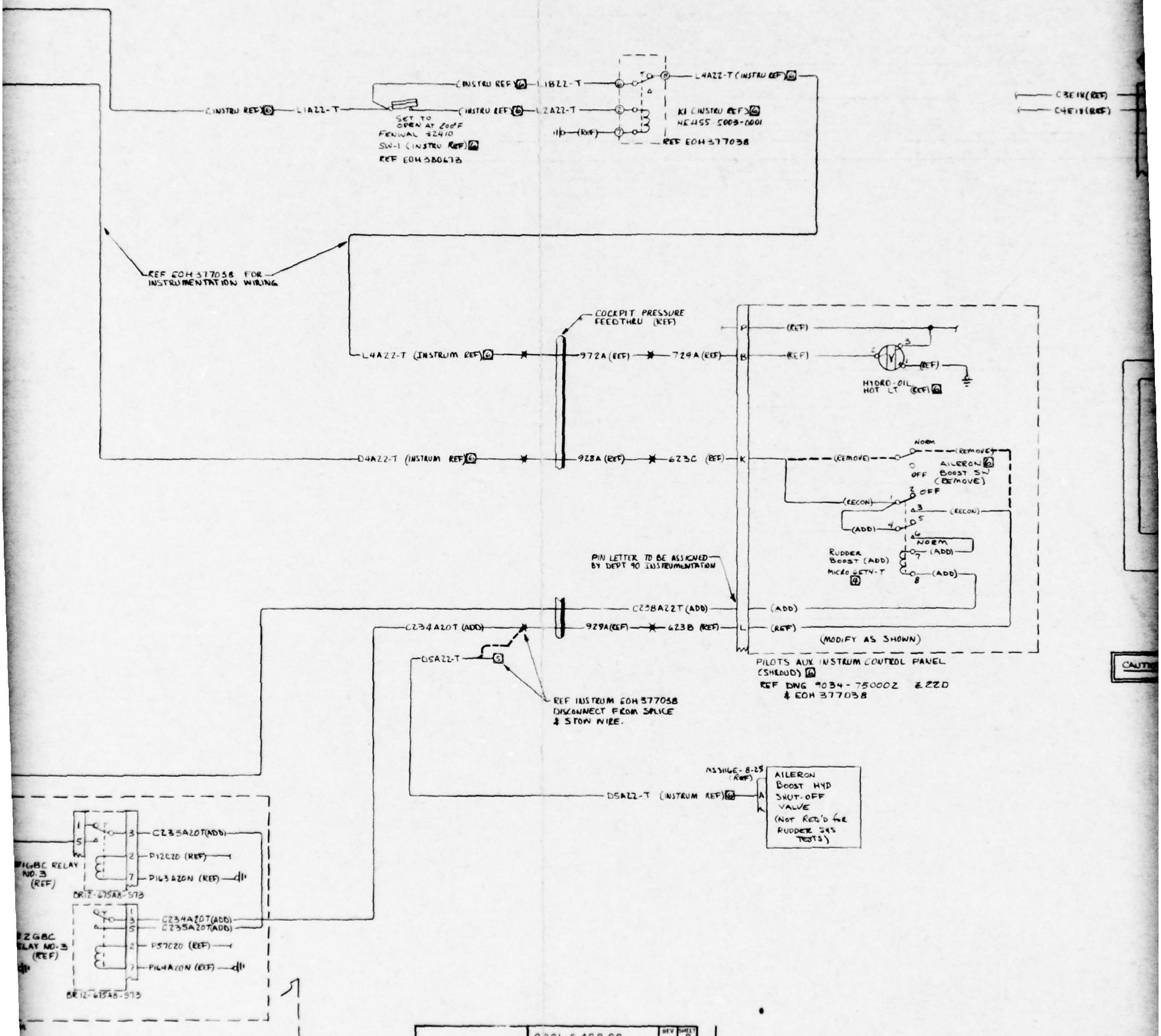
4	3	2	1	12

FORM 311-G-4 REV 6-70

5



H
G
F
E
D
C
B
A
28VDC PRI BUS
5A
L191A20(REF)
L1A22-T (INSTRU REF)
D4A22-T (INSTRU REF)
(REMOVE)
AFT CONSOLE LTS
28VDC MON BUS
5A
A76A20 (REF)
D4A22-T (RECON)
MARK 6 FIRE CONT
DC CIRCUIT BREAKER PANEL
288-545514-21
288-545531-5 BUS (REF)
NO.1 REVERSE CURRENT CUTOUT RELAY
NO.2 REVERSE CURRENT CUTOUT RELAY
P300A0T (ADD)
288-545531-7 BUS(REF)
60A
NO.1 INVERTER PWR
DC PWR DIST PANEL FSTA 170 LH
288-545511 MODIFIED TO
310-540052-31
200A
C239A0T (ADD)
HYD PUMP MOTOR C/B (ADD) 4
MS39064-2 1 REQD
C/B BKT ASSY
EDH382681-1, -3 & -5
FUS STA 162 LH
THERMAL SW TERMINAL LOCATED UNDER NEG (−) PUMP MOTOR TERMINAL
THERMAL SWITCH
C238A22T (ADD)
M
+
C240A0T (ADD)
−
C241A0NT (ADD)
A1
A2
C239A0T (ADD)
X1
C232B20T (ADD)
X2
C237A20NT(ADD)
HYD PUMP MOTOR ASSY
ABEX PG76-0486
FSTA 285 ¢
HYD PUMP MOTOR RELAY
8 MS24171D1 (ADD) 1 REQD
FSTA 270 ¢ (REF EDH382681)
TERMINAL DESIGNATORS + & − ARE LOCATED ON END OF TERMINAL STUDS.
HYD PUMP MOTOR GROUNDING TAB (ADD) EDH382681-9
FSTA 280 LH
AN6-13A 1 REQD
LD153-0011-0017 2 REQD
MS21042-6 1 REQD
MS35338-46 1 REQD
AN961-616L 1 REQD
C232A20T(ADD)
C232C22T(ADD)
#1GBC RELAY NO.3 (REF)
HE414-0003-0001 1 REQ (ADD) 4
A3
A2
A1
1
3
5
SEE SHT 1 ZONE 20E
#2GBC RELAY NO.3 (REF)
2
7
C233A22NT (ADD)
AFCAS CONT RELAY
BR12-675A8-573 1 REQD
KB (ADD) 4
RELAY PANEL ASSY FSTA 125 LH
310-545549-11
LEFT HAND EQUIP BAY
40
39
38
37
36

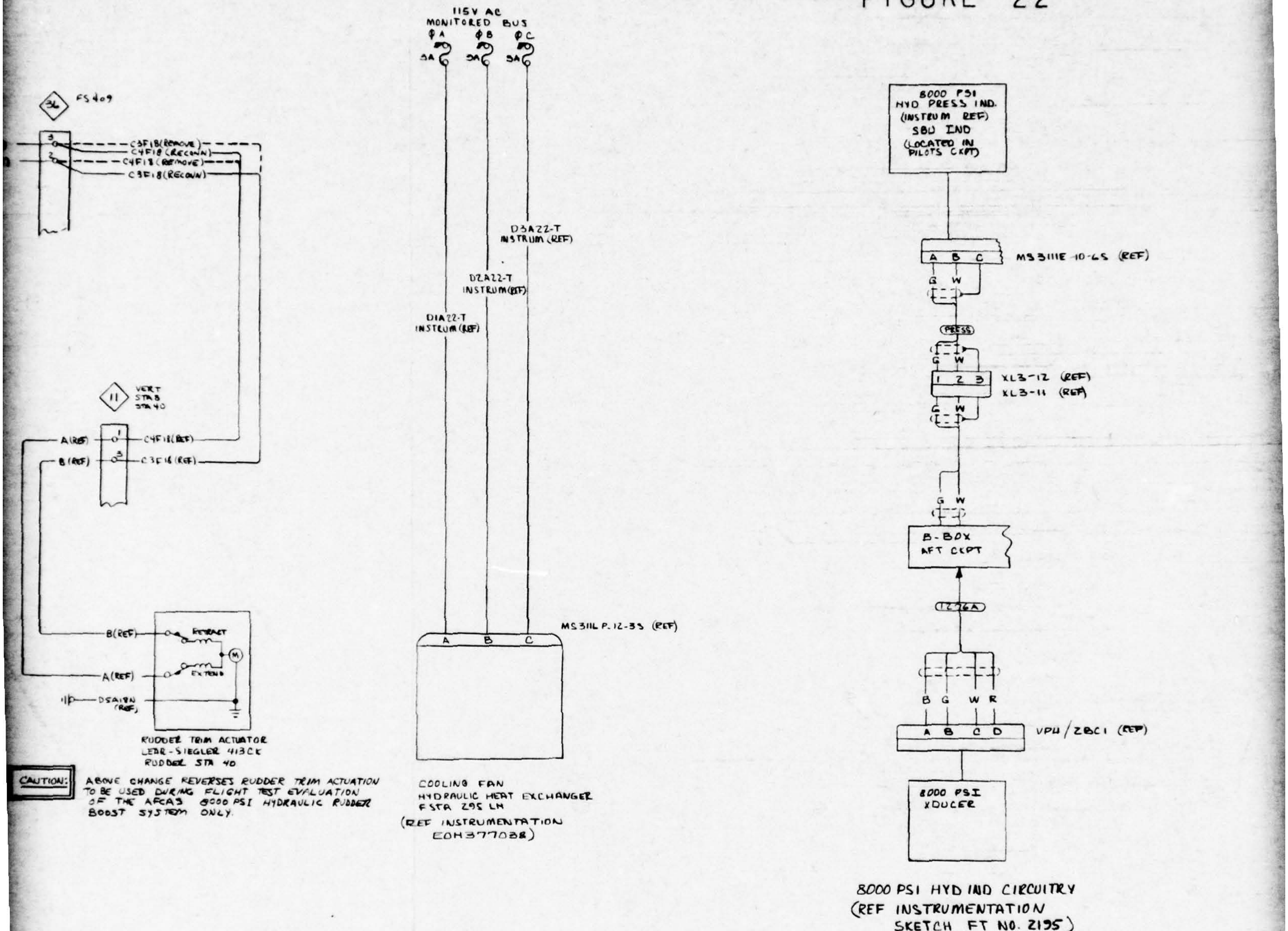


8691-5466 06 | REV | SHEET 2

35 | 34 | 33 | 32 | 31

ZONE	LTR	DESCRIPTION
		1 MAY BE REWORKED 2 CANNOT BE ... 3 RECORD CHANGE 4 NON SHOP PRAC... 5 PARTS MADE OR

FIGURE 22



WIRING DIAGRA[M]
AFCAS POWER CO[...]

Rockwell International Corporation, Columbus Aircraft Division, Columbus, Ohio 43216

SIZE	FSCM NO	
J	89372	8691-5...

DWN BY: M. TAY, JR.
DATE: 1-6-78
SCALE

30 | 29 | 28 | 27 | 26 | 25

2

3

I 12

REVISIONS

SCRIPTION	DISPN	DATE	APPROVED
2 CANNOT BE REWORKED 4 NON SHOP PRACTICE MADE ON			

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8691-546606

GRAM -
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FORM 311-G-21 REV 6-76

3 8691-546606 SHT 2

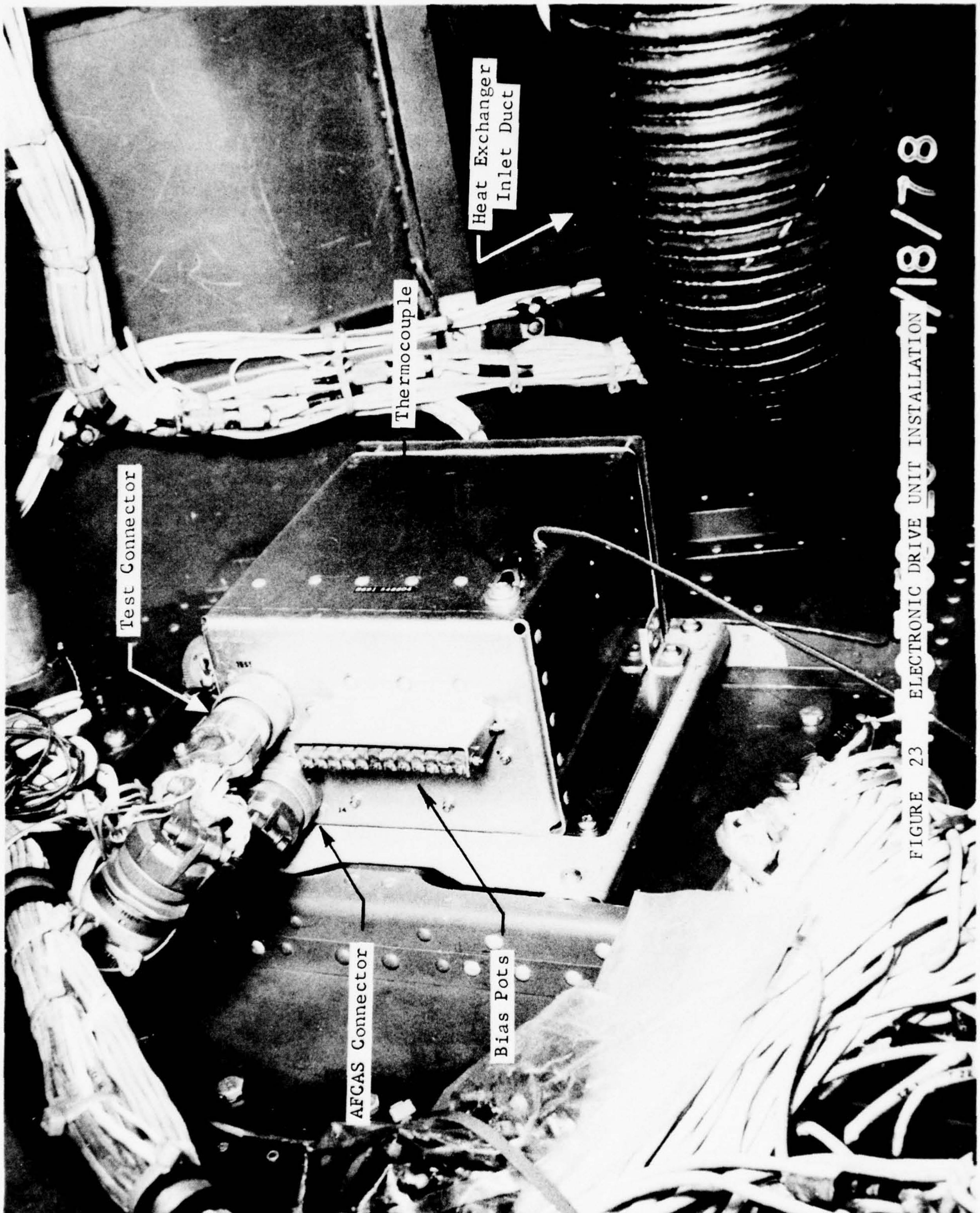


FIGURE 23 ELECTRONIC DRIVE UNIT INSTALLATION

3.5 INSTRUMENTATION

The T-2C was equipped with several flight data acquisition systems. Two were used in the AFCAS program: (1) an 18 channel telemetry system, and (2) a 21 hole photo recorder system. The telemetry oscillator package was located in the aft cockpit seat area; the photo recorder was installed inside the nose, Figure 24.

Telemetry data were recorded at the CAD Telemetry and Data Processing Center where a UHF receiving/tracking system provided real-time data acquisition and direct read-out on strip charts, Figure 25. Audio communication with the pilot was available for convenience and safety monitoring.

Pilot instrumentation controls were located above the cockpit instrument panel, Figure 26, and on the control stick. Data in the two recording systems were related by means of correlator numbers printed on the photo recorder film, and correlator blips on the TM strip chart. A correlator counter could be read by the pilot for reference purposes.

New equipment installed to permit the pilot to monitor and control the AFCAS system were:

- An indicator was provided for direct readout of the motor/pump discharge pressure

- A switch was provided to turn the motor/pump unit "on" and "off"

- An "oil hot" light was set to illuminate when hydraulic fluid in the motor/pump suction line exceeded approximately +200°F (93°C)

Flight data parameters instrumented in the T-2C for the AFCAS program are listed on Table II. Operating range, accuracies, and response capabilities are also listed.

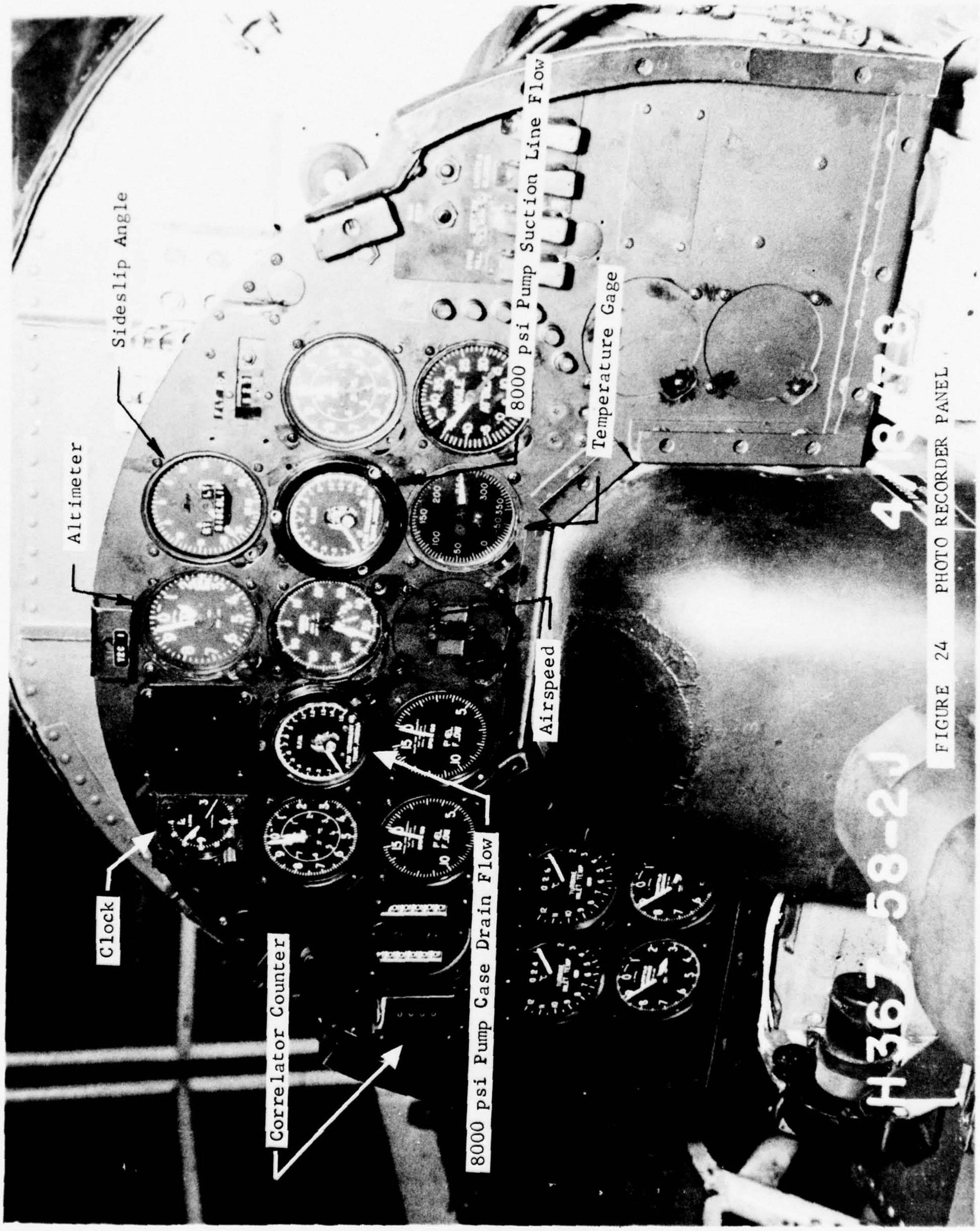


FIGURE 24 PHOTO RECORDER PANEL

FIGURE 25 TELEMETRY AND DATA PROCESSING CENTER

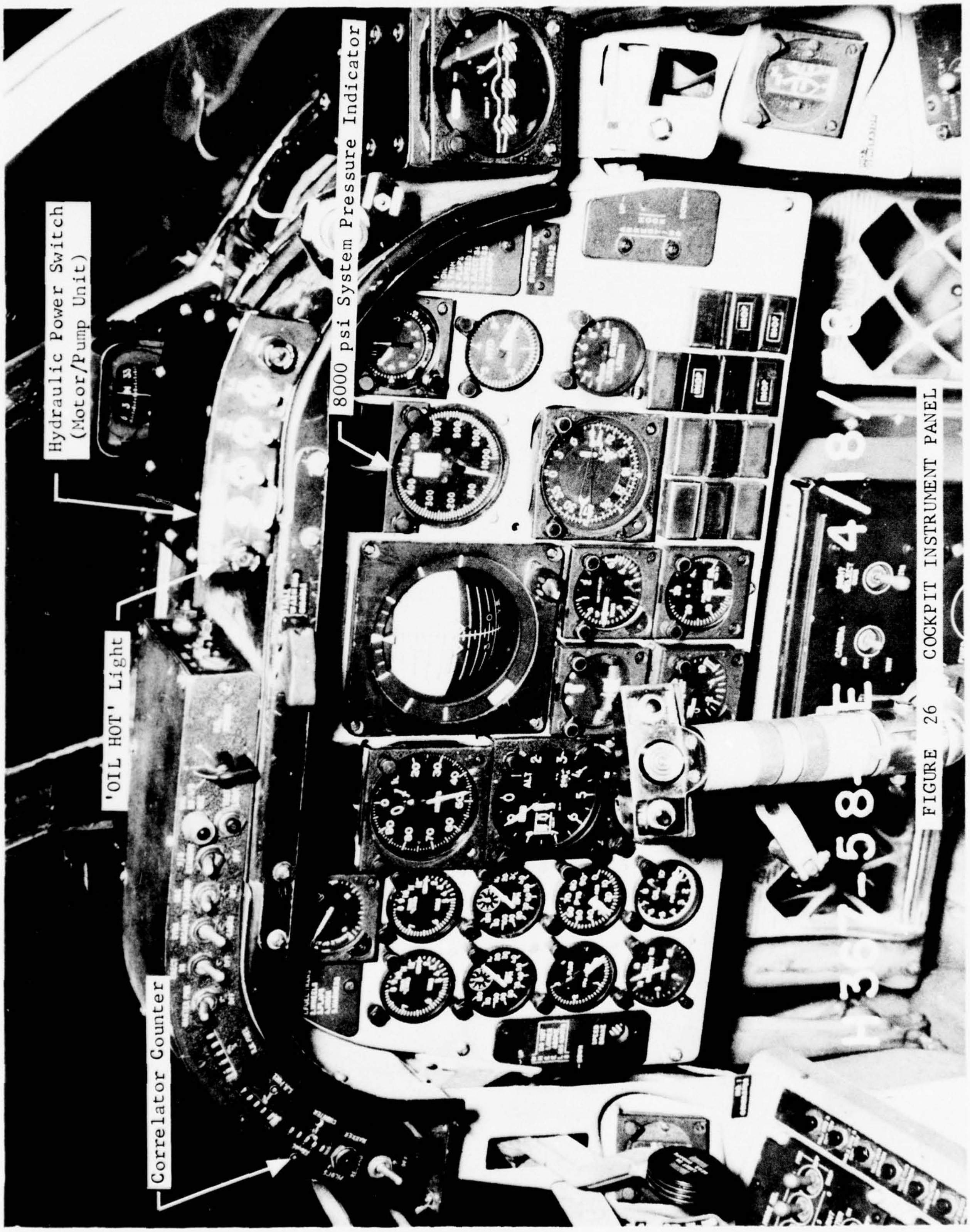


FIGURE 26 COCKPIT INSTRUMENT PANEL

TABLE II LIST OF INSTRUMENTATION

PARAMETER	RANGE	ACCURACY	READOUT RESPONSE
PHOTO RECORDER SYSTEM			
1. Time	N/A		
2. Airspeed	50 to 500 kts (26 to 260 m/s)		
3. Altitude	0 to 50,000 ft. (15.2 km)		
4. RPM, L/R Engines	0 to 8,000 RPM		
5. Fuel Counters, L/R Engines	N/A		
6. Correlation and Pilot Marker	N/A		
AFCAS Parameters			
7. Flow, Pump Case Drain Line	0 to 1.0 GPM (0 to 3.78 L/m)	±2%	2 Hz
8. Flow, Pump Suction Line	0 to 1.0 GPM (0 to 3.78 L/m)	±2%	2 Hz
9. Temp, EDU Housing	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
10. Temp, Fuselage Compartment Air	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
11. Temp, Pump Suction Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
12. Temp, Pump Case Drain Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
13. Temp, Heat Exchanger Inlet Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
14. Temp, Heat Exchanger Outlet Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
TELEMETRY SYSTEM			
1. Correlation and Pilot Marker	N/A		
2. Temp, Outside Air	-76 to +140°F (±60°C)		
3. Acceleration, Normal (Vertical)	-5 to +10g		
AFCAS Parameters			
4. Press, Pump Suction Line	0 to 50 psia (0 to .3 MPa)	±3%	100 Hz
5. Press, Pump Discharge Line	0 to 10,000 psig (0 to 69 MPa)	±3%	100 Hz
6. Press, Pump Case Drain Line	0 to 100 psia (0 to .6 MPa)	±3%	100 Hz
7. Position, Rudder	±12°	±2%	100 Hz
8. Position, AFCAS Transducer #1	±10 volts DC	±2%	100 Hz
9. Position, AFCAS Transducer #2	±10 volts DC	±2%	100 Hz
10. Force, AFCAS Transducer #1	±2.5 volts DC	±2%	100 Hz
11. Force, AFCAS Transducer #2	±2.5 volts DC	±2%	100 Hz
12. Current, AFCAS Motor Coil #1	±1.0 volts DC	±2%	100 Hz
13. Current, AFCAS Motor Coil #2	±1.0 volts DC	±2%	100 Hz
14. Current, AFCAS Motor Coil #3	±1.0 volts DC	±2%	100 Hz
15. Current, AFCAS Motor Coil #4	±1.0 volts DC	±2%	100 Hz
16. Temp, Oil Hot Light (+200°F)	N/A		

4.0 PREFLIGHT TESTS

4.1 LABORATORY TESTS

4.1.1 Motor/Pump Unit

Pump - The pump was removed from the motor for performance testing, and mounted on a torque meter attached to a varidrive. The test system is described in Reference 12. Data were taken to permit comparisons with rated performance prior to pump de-stroking. Data covering rated performance (from Reference 12) and current performance are shown on Table III. The rework lowered heat rejection approximately 12 percent during zero discharge flow operation (the most prevalent operating mode). Data taken under worst case operating conditions are also given on Table III. Heat rejection increased slightly under these conditions, but this would not significantly affect AFCAS performance.

Motor - The motor was powered with a Hobart 28 volt DC motor-generator rated for 1000 amperes. No. 1 gage stranded copper wire was used between the motor-generator leads and the test motor. Current was measured using a 600 ampere 50 mv shunt, millivolt meter, oscilloscope, and oscillograph with a 240 Hz galvanometer. No-load and load (with pump) operating data were recorded. The results are summarized below:

	No Load	With Pump*
Speed, rpm	8640	8100
Peak starting current, amperes	1200	1200
Starting current >1000 amperes, sec	0.035	0.035
Running current, amperes	20	140
Time to reach full speed, sec	0.4	0.4
Time to stop after shut-down, sec	--	1.1

*Pump powered AFCAS hydraulic system. At start-up, system pressure was zero; after start-up pressure was 8000 psi.

TABLE III

PUMP PERFORMANCE COMPARISONS

PUMP M/N AP1V-106, S/N 151353 PUMP SPEED: 7330 RPM

	MAX. DISPL., CIPR	INLET FLUID TEMP., °F/°C	RESERV. PRESS., PSIG	PUMP CASE PRESS., PSIG	DISCH. PRESS., PSIG	DISCH. FLOW, GPM	CASE FLOW, GPM	CASE DR. FLUID TEMP., °F/°C	HEAT REJECT., BTU/MIN
*	.100	110/43	30	50	7500	3.22	.20	184/84	78
**	.016	110/43	30	50	7500	.75	.35	170/77	89
***	.016	110/43	12	80	7500	.68	.29	187/86	100
	.100	180/82	30	50	7500	3.17	.30	239/115	72
	.016	180/82	30	50	7500	.50	.55	230/110	116
	.016	180/82	12	80	7500	.48	.465	246/119	124
	.100	110/43	30	50	8000	0	.57	175/79	142
	.016	110/43	30	50	8100	0	.44	180/82	124
	.016	110/43	12	80	8100	0	.39	202/94	139
	.100	180/82	30	50	8000	0	.75	236/113	179
	.016	180/82	30	50	8100	0	.66	240/116	157
	.016	180/82	12	80	8100	0	.57	260/127	171

* Rated performance. Data taken from Reference 12.

** De-stroked configuration. Same operating conditions as Reference 12 data.

*** 12 psig reservoir pressure and 80 psig pump case pressure are worst case operating conditions.

Metric Conversions:

PSIG X 6895 = Pa

GPM X 3.785 = L/m

BTU/MIN X 17.58 = W

Motor operation was observed to produce significant noise on the supply voltage. Supply voltage ripple was less than ±0.2 volts DC with the motor off. With the motor running, voltage noise covered a band from approximately 22 to 32 volts DC. The two 24 volt DC batteries in the T-2C were anticipated to be an effective filter which would reduce the noise level in the aircraft installation. To verify this, a 24 volt DC aircraft battery was paralleled into the laboratory system. The supply voltage noise, with the motor running and the battery filter, was reduced to a band from approximately 26 to 29 volts. Two batteries further improved noise filtering, reference Section 4.3.

Motor surface temperature was monitored during simulated flight testing, Section 4.1.4. The temperature stabilized at 60°F (33°C) above ambient after 1.5 hours of driving the AFCAS hydraulic system.

4.1.2 Rudder Actuator

The actuator has three control elements--force motor, flow control valve, and position feedback transducers. Operating characteristics of each of these units were evaluated.

Force Motor - Motor output force and displacement vs. input current were measured using the control valve and housing discussed in Reference 3. (The closed-end design of sleeve P/N SO 4262-03-11 prohibited use of the rudder actuator valve, Reference 4.) Motor output force was measured with a hand-held spring scale applied directly to the spool. Motor output arm displacement was sensed by a dial indicator placed on the opposite end of the spool. The four coils in the motor were connected in series, and an adjustable DC power source was used to apply various amperage levels. Current was measured with a clip-on type DC ammeter. Specific values of current were applied and the force required to position the spool at given displacements from null were measured. The results are presented on Figure 27.

Maximum output force at null was approximately 40 lb (178 N). Saturation began at ±0.3 amperes and approached 100 percent at ±0.8 amperes. The restoring force available at ±0.020 in. (0.76 mm) displacement averaged 62 lb (275 N). (±0.020 in. was rated spool displacement although displacements up to ±0.040 in. were possible.) Motor gain at ±0.020 in. displacement and zero output force averaged 0.033 in/amp (.85 mm/amp) for the coils connected in parallel; the design value was 0.035 in/amp, Figure 19.

Flow Control Valve - The valve was tested in its housing on the rudder actuator. External ports in the housing were utilized to interconnect the actuator cylinder chambers (C1 and C2). This permitted continuous flow to be controlled through the actuator. A needle valve was put in the line connecting C1 and C2, and gages were installed to measure chamber pressures. Flow was measured with a turbine meter in the actuator return

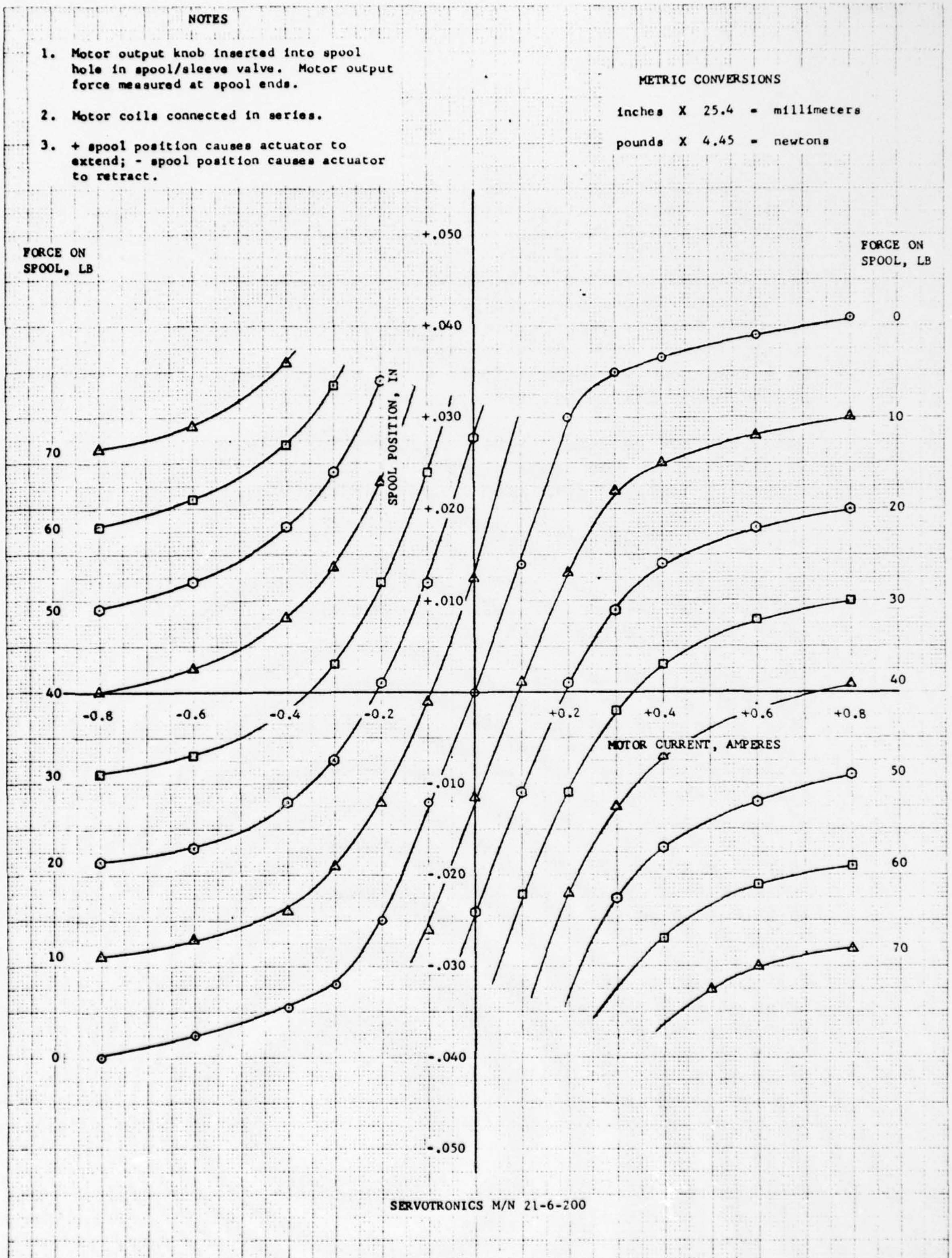


FIGURE 27 FORCE MOTOR OPERATING CHARACTERISTICS

line. The valve spool was driven by Servotronics motor M/N 21-6-200 which in turn was driven by an adjustable DC power source. Supply pressure was 8000 psi (55 MPa); inlet fluid (MIL-H-83282) temperature was +110 $\pm$5°F (43 $\pm$ 3°C). Three performance characteristics of the valve/motor assembly were determined: flow gain, pressure gain, and internal leakage.

Flow Gain. The data on Figure 28 show input current vs. output flow characteristics of the motor/valve operating open loop. Flow gain was 4.1 gpm/amp (15.5 L/m per amp) for the extend direction (piston motion), and 2.1 gpm/amp (7.95 L/m per amp) for retraction. The design value was 2.3 gpm/amp (8.70 L/m per amp), Figure 19.

ΔP forces on the spool ends were believed to cause the asymmetrical flow gain. Spool/sleeve type valves usually have exit flow patterns at each end of the spool that are similar, providing approximately equal ΔP forces across the spool for each flow direction. (A hole is sometimes drilled length-wise through the spool to equalize these forces.) The AFCAS valve was designed with one end closed (return flow through the sleeve periphery), one end open (return flow around the large knob on the spool), and no hole through the spool spindle. The closed end of the sleeve housed a position adjustment feature which permitted mechanical alignment of the valve and motor nulls. When return flow was around the spool knob (actuator piston extending), aiding ΔP forces were developed, increasing flow gain, Reference 3. When return flow went through holes in the sleeve periphery, the aiding ΔP forces were not present. Although the motor/valve current/flow gain was asymmetrical, tests on the actuator assembly reported in Section 4.1.3 indicated this discrepancy caused no significant degradation in performance.

Pressure Gain. Pressure gain was determined with ports C1 and C2 blocked. Motor/valve pressure gain was 220,000 psi/amp (1.5 GPa/amp), Figure 29. This value was considered satisfactory. The small null off-set was due to a slight misalignment between the pressure null of the valve and mechanical null of the motor; closed loop operation effectively eliminated this.

Internal Leakage. Internal leakage peaked near null and was 0.058 gpm (220 cc/min). The design value was 0.034 gpm (130 cc/min). The higher than desired leakage was attributed to manufacturing discrepancies. The extra leakage--90 cc/min--was not considered detrimental to system performance.

Feedback Transducers - Position transducer output voltage (e_{fb}) vs. core displacement was measured over the range of actuator piston travel ($\pm$1.75 in. or $\pm$4.44 cm). Data covering piston travel vs. load on the force transducer (F_2) were also taken. The data were linear and were summarized as follows:

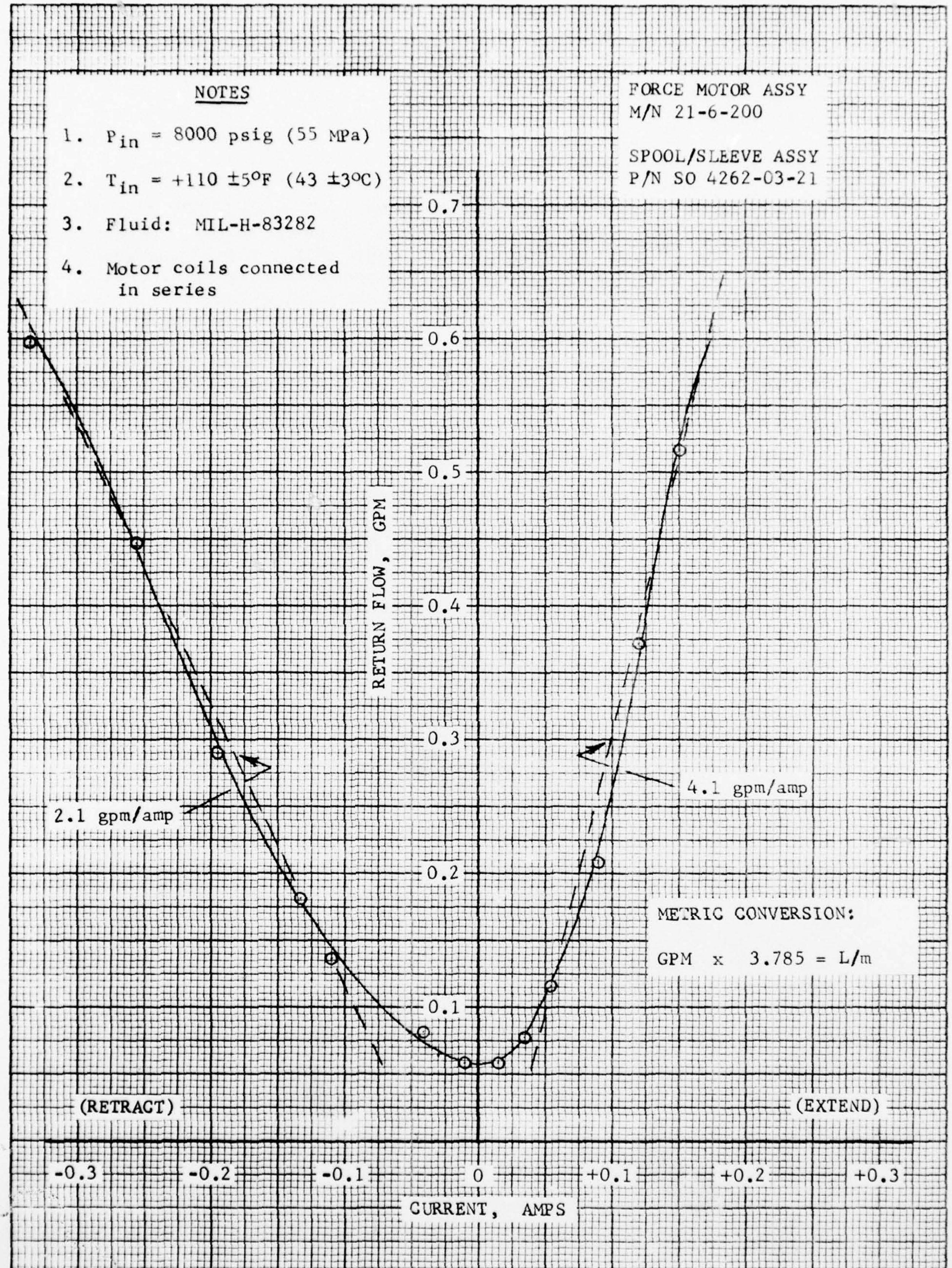


FIGURE 28 FLOW GAIN

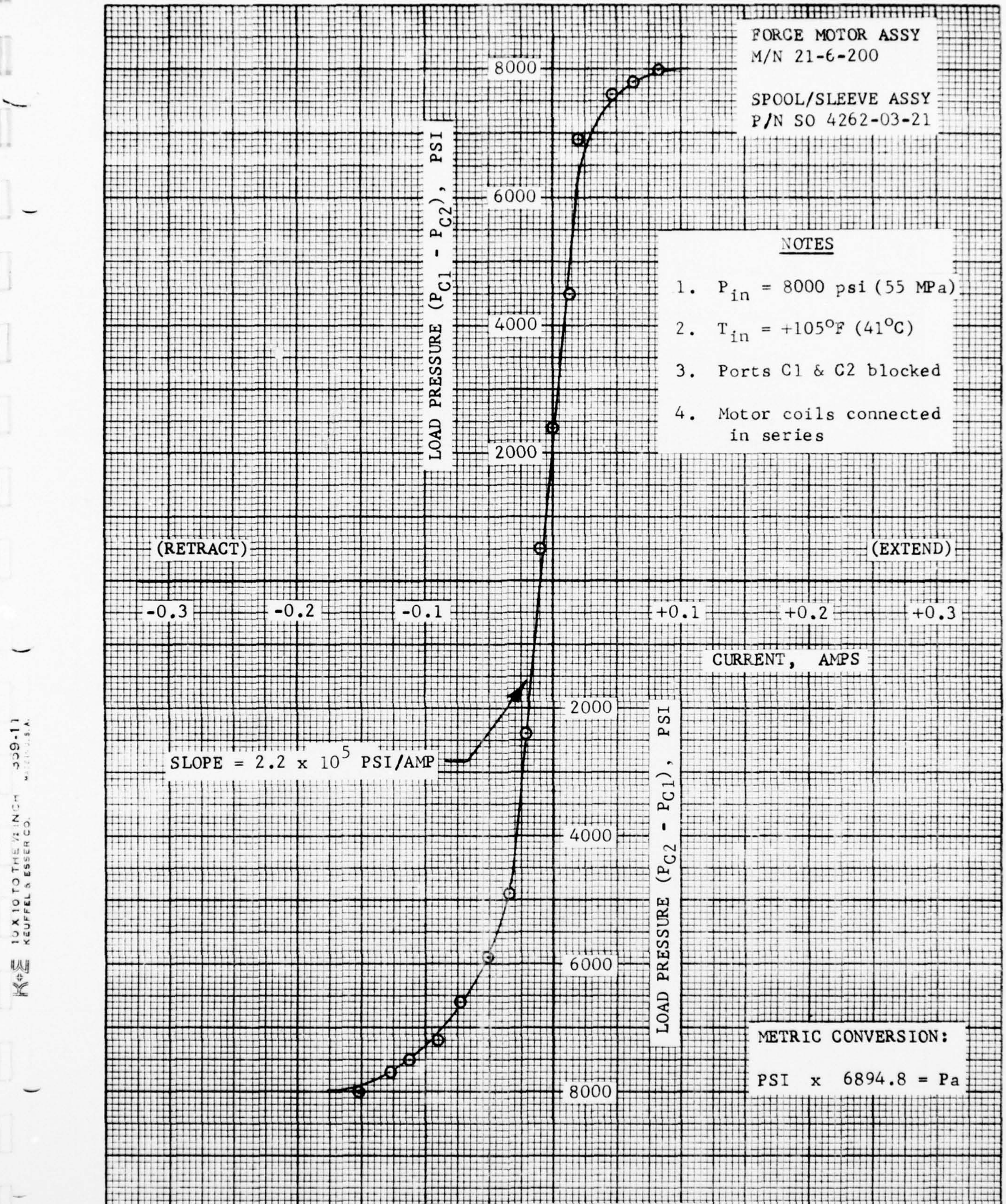


FIGURE 29 PRESSURE GAIN

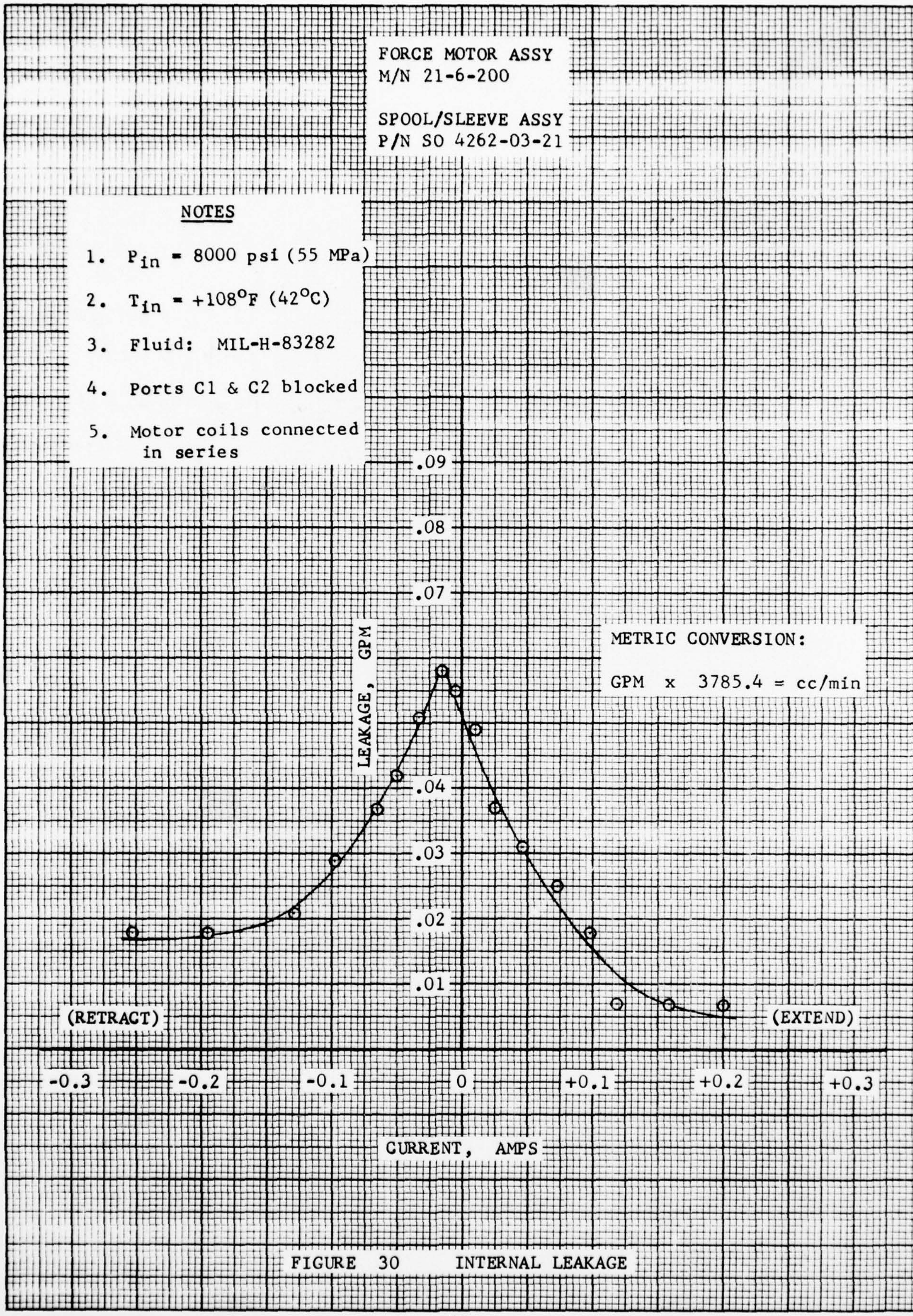


FIGURE 30 INTERNAL LEAKAGE

Position Transducer	e_{fb} vs. Displacement	F2 vs. Displacement
#1 (S/N 373)	4.7 V/in (1.8 V/cm)	116 lb/in (20.3 kN/m)
#2 (S/N 374)	4.9 V/in (1.9 V/cm)	112 lb/in (19.6 kN/m)

4.1.3 System Integration

The laboratory setup integrating all major components to be installed on the T-2C is shown on Figures 31 and 32. The system contained all the equipment listed on Table I plus the electronic drive unit, force transducer, T-2C hydraulic system reservoir, oil-to-water heat exchanger, and two 10 micron (nominal) filters. An oil-to-air heat exchanger used in the aircraft test installation was not employed in the laboratory setup.

The 8000 psi (55 MPa) laboratory system is depicted schematically on Figure 33. The T-2C 3000 psi (21 MPa) hydraulic system (pump, aileron actuator, elevator actuator, utility functions, etc.) were not included in the laboratory setup because potential benefits derived from testing a complete system did not warrant the added expense. Temperature, pressure, and fluid flow instrumentation were installed at several locations in the setup; this equipment did not simulate flight test instrumentation, Section 3.5. Hydraulic line lengths and sizes used in the aircraft test installation were duplicated (as nearly as practical) in the laboratory setup. Tubing bends were not simulated, however, all elbow type fittings employed in the aircraft were put in the laboratory system. High pressure tubing was 1/4 x .025 in. 21-6-9 CRES. All 8000 psi tubing connectors were standard MS flareless fittings. (8000 psi fittings used in the aircraft were "Dynatube" series.) Static seals were MS 28778 O-rings. The system contained approximately 2.0 gal (7.6 L) of MIL-H-83282 fluid. The reservoir was placed 28 in. (71 cm) below the pump suction port to simulate aircraft orientation.

Fluid flow in the pump case drain and actuator return lines was measured by turbine meters with readout on frequency counters. Static pressures were monitored with bourdon tube dial gages teed into the pump suction, discharge, and case drain lines. Dynamic pressures were recorded on a high response oscillograph using strain gage type transducers plumbed in the pump discharge and actuator return lines. Fluid temperatures were sensed by thermocouples at seven locations: pump suction line, case drain line, actuator return line, heat exchanger inlet and outlet ports, pump motor surface, and ambient air. Temperature readout was on a multi-channel, selector-button type indicator. Fluid temperature stabilization was achieved by means of a duration-adjusting type controller and the oil-to-water heat exchanger.

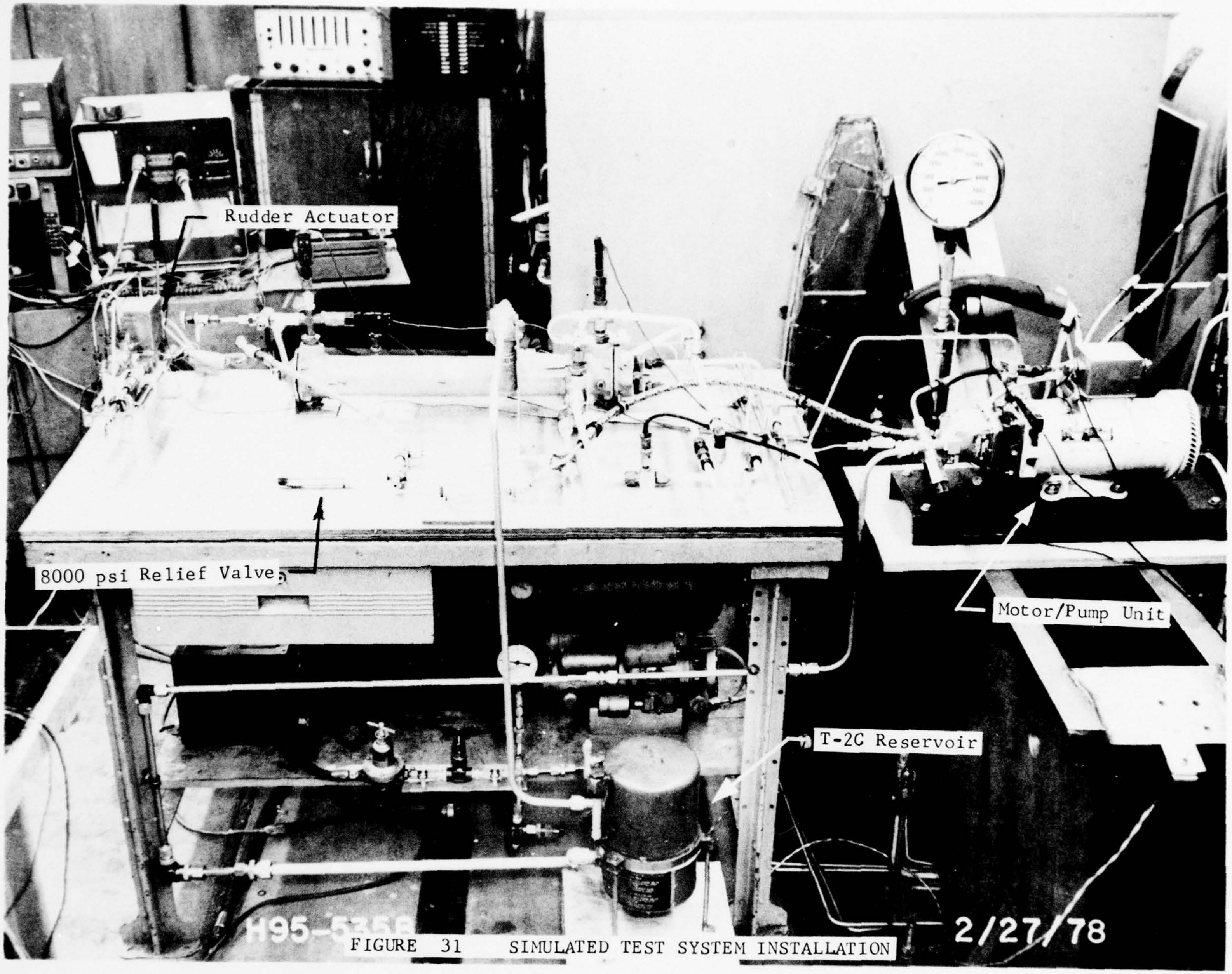


FIGURE 31 SIMULATED TEST SYSTEM INSTALLATION

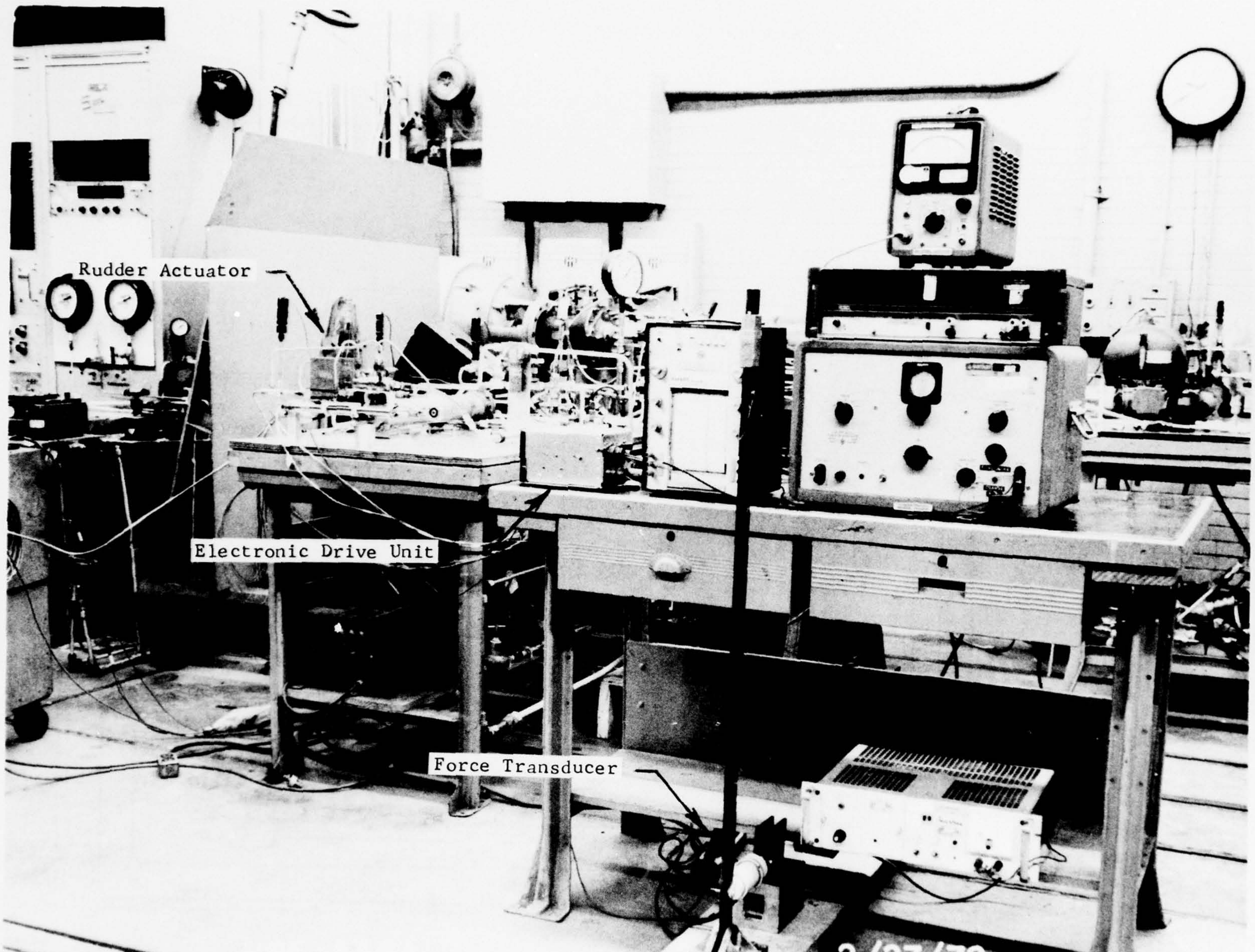


FIGURE 32 LABORATORY INSTRUMENTATION

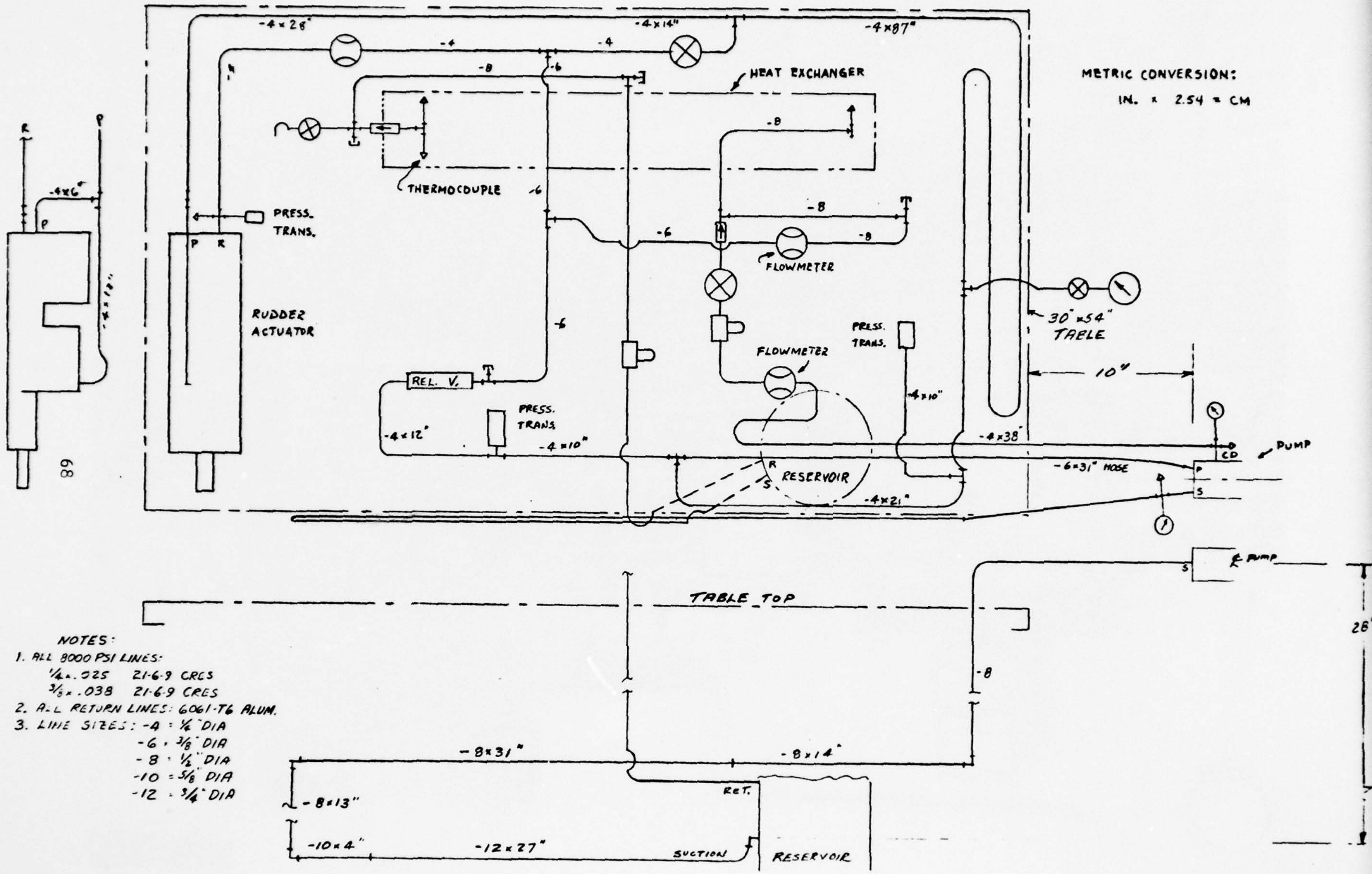


FIGURE 33 SCHEMATIC DIAGRAM OF SIMULATED TEST SYSTEM HYDRAULIC INSTALLATION

Electrical components in the system are shown on Figure 32. The force transducer was installed in a fixture with a lever for applying simulated rudder pedal loads. Laboratory harness was made for interconnecting the EDU with the rudder actuator and force transducer. A terminal board was built which permitted voltage checks at 24 test points within the EDU. A function generator was used to apply sinusoidal and step commands to the EDU. Input and output (command signal and actuator piston position) were recorded simultaneously on a dual channel strip chart for response evaluations. A 400 cycle 110 volt AC power supply, digital voltmeter, and clip-on DC ammeter completed the instrumentation.

Initial Checkout Tests - The first tests were continuity and circuit checks on the EDU. Several minor wiring errors and omissions were found and corrected. Power was applied and voltage checks were made at 24 test points, Figure 20. After all circuitry was confirmed, and EDU operation was determined to be satisfactory, the transducer nulls were adjusted. The position transducer cores were set so that when the actuator piston was mid-stroke, transducer output was less than ±0.100 volts DC. The force transducers were removed from the housing and their cores were adjusted so that, with no load applied, transducer output was less than ±0.125 volts DC. With all the transducers at null, the current in each of the motor coils was then adjusted to zero by external bias pots on the EDU.

System Integration Tests

Hydraulic System Stability - Persistent pressure oscillations were observed in the 8000 psi (55 MPa) circuit during initial start up of the system. The oscillations were 800 psi (5.5 MPa) peak-to-peak at 25 Hz and considered excessive. Attempts were made to attenuate the oscillations by adding various amounts of fluid volume at different locations in the system. Eight configurations were tried with no success. After consultation with the pump manufacturer (Abex), it was decided to turn the pump compensator spring end-for-end and determine if variations in the squareness of the ground ends were affecting stability. This was done and the stability problem was corrected; discharge pressure was a steady 8000 psi (55 MPa) (no oscillations) and pump ripple was less than ±100 psi (.7 MPa).

Pressure Surges - Magnitudes of peak pressures measured during system start-up and actuator hard-over commands are summarized below. The surges were well below the 120 percent (9600 psi) maximum allowable, Reference 8.

Location	Start-Up	Hard-Over Commands
Pressure Line (60 in. from pump)	8400 psi (58 MPa)	8350 psi (57.6 MPa)
Return Line (at rudder actuator)	12 psig (83 kPa)	50 psi (345 kPa)

System Temperatures - Based on data reported in Reference 13, fluid temperature in the pump suction line could be expected to range from +130 to +140°F (54 to 60°C). Results of the laboratory test with fluid temperature stabilized at +132°F (57°C) in the suction line are summarized below. The temperatures, flows, and heat removed were all considered satisfactory.

Pump Suction	Pump Case Dr.	Actuator Return	Ambient Air	Pump Case Dr.	Actuator Return	Heat Removed By Heat Exchanger
+132°F	+214°F	+151°F	+85°F	0.56 gpm	0.07 gpm	157 BTU/min
+57°C	+101°C	+66°C	+29°C	2110 cc/min	275 cc/min	2.7 kW

System Operation - Manual operation of the force transducer, reference Figure 32, provided a subjective indication of overall system performance. Actuator piston motion was controlled positively, with little overshoot and little apparent hysteresis. Sensitivity was excellent. (Less sensitivity could be obtained, if desired, by simple adjustments in the EDU.) Minimum time for full stroke (24° rudder deflection) was approximately 0.5 sec. Pump speed was noted to sag slightly during actuator stroking (pump loaded) and return to full speed when the pump was unloaded. No external leakage was observed except for normal wetting of the actuator piston rod.

The general consensus of several engineers and a pilot who operated the force transducer lever was the laboratory system functioned very well.

Response Characteristics - Overall system response was determined from square wave, saw tooth, and sinusoidal inputs applied to the EDU by a function generator while the rudder actuator was pressurized at 8000 psi. (Force transducer inputs were not used.) The input signal and output piston motion were recorded simultaneously.

Response to 0.5 Hz square wave and saw tooth inputs are shown on Figure 34. Slight rounding at the saw tooth peaks was due to control valve dead band; this was not significant considering the amplitude and frequency of the data. Overshoot peaks on the square wave were near optimum.

Frequency response was determined for three amplitudes at 0.5 Hz: ±.050, ±.100, and ±.200 in. (±1.27, ±2.54, and ±5.08 mm). The 3 dB bandwidth for ±.050, ±.100, and ±.200 in. amplitudes were 9, 13, and 11 Hz, respectively, Figure 35.

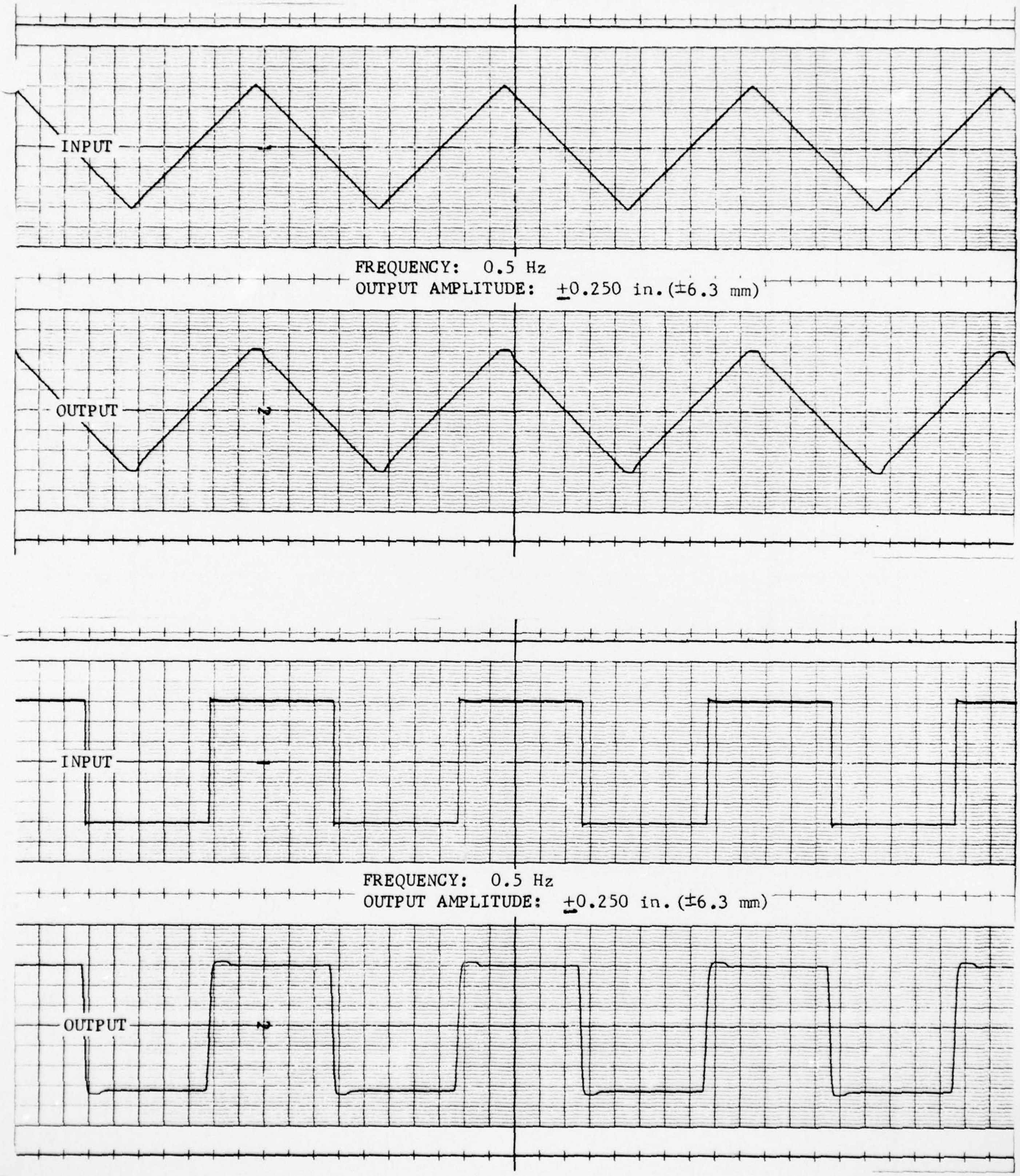


FIGURE 34 SAW TOOTH AND SQUARE WAVE RESPONSE

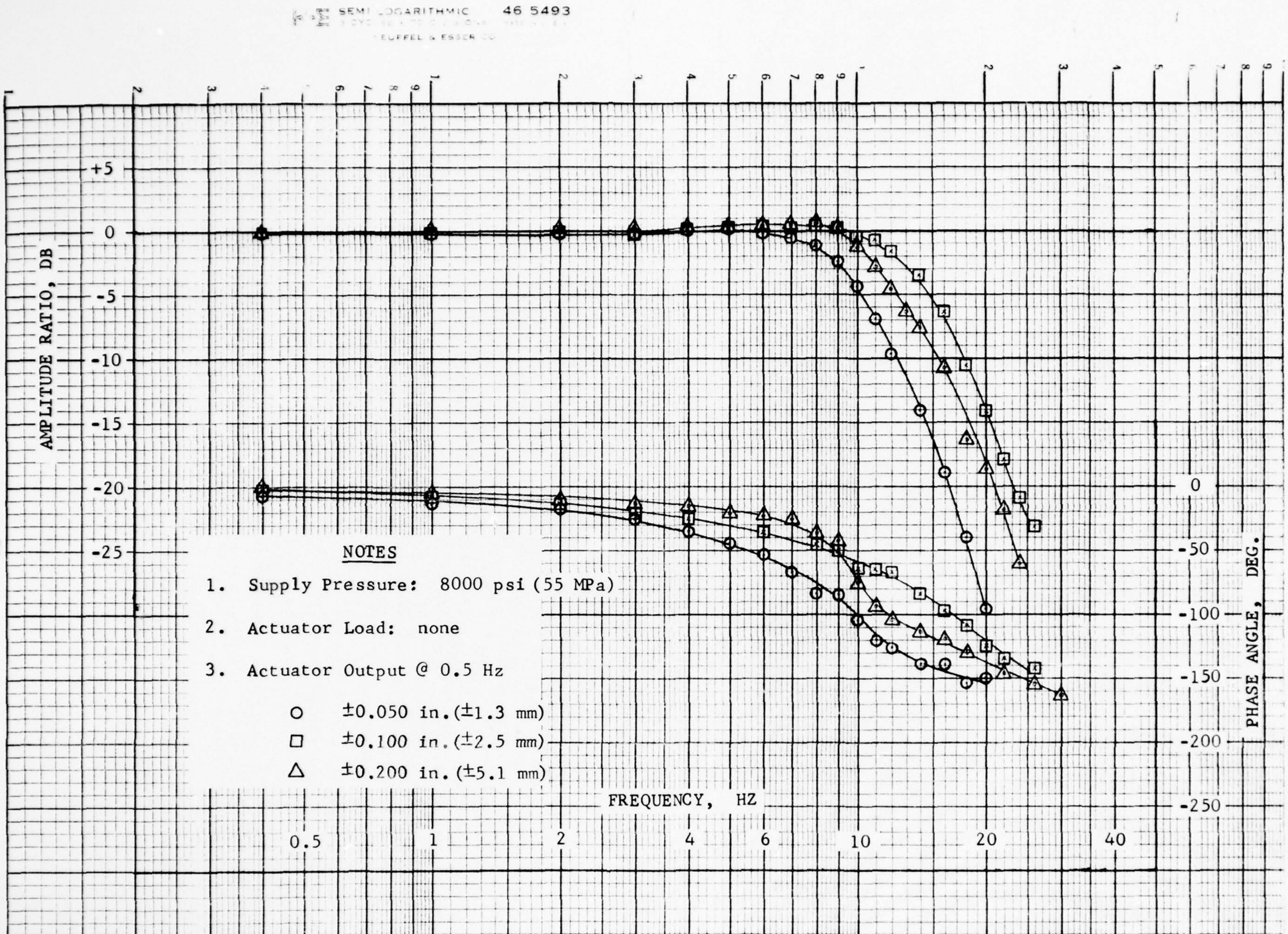


FIGURE 35 SYSTEM FREQUENCY RESPONSE

Higher response could be achieved by adjusting loop gain. Because of T-2C directional system dynamics the AFCAS response utilized was approximately 3 Hz. This bandwidth proved entirely satisfactory for the test installation, Section 5.0.

4.1.4 Simulated Flight Testing

A total of approximately 10 flight hours were to be accumulated on the AFCAS test installation, Section 5.0. The laboratory simulation consisted of six 1-1/2 hour "flights". The following schedule profiles a typical flight:

Flight Phase	Duration, Min.	Rudder Operation
Ground checkout and taxi out	15	Periodic
Take-off	7.5	Periodic
Cruise	45	Periodic
Full-power flight	7.5	Periodic
Landing and taxi in	15	Periodic
Total	90	

All tests were conducted with minimum reservoir pressurization (12 psig/83 kPa) and maximum case drain pressure (80 psig/551 kPa). Pump suction line fluid temperature was maintained in the range of +130 to +140°F (+54 to 60°C). The following parameters were tracked during the test:

(1) Pump case drain flow
(2) Actuator null flow
(3) External leakage (pump and actuator)
(4) Pump motor current
(5) Actuator motor null current
(6) Pump case drain filter debris (patch test)

Performance data taken before and after six 1-1/2 hour simulated flights are summarized on Table IV.

TABLE IV

SIMULATED FLIGHT PERFORMANCE SUMMARY

	BEFORE TEST	AFTER SIX "FLIGHTS"
Pump Case Drain Flow (at +212°F/100°C)	0.53 gpm (2000 cc/min)	0.56 gpm (2120 cc/min)
Actuator Null Flow (at +160°F/71°C)	0.07 gpm (270 cc/min)	0.07 gpm (275 cc/min)
Pump External Leakage	None	None
Actuator External Leakage	None	Trace (at rod seal)
Pump Motor Current (after warm-up)	156 amperes	144 amperes
Actuator Motor Null Current		
Coil #1	0	+0.02 ampere
Coil #2	0	+0.03 ampere
Coil #3	0	-0.01 ampere
Coil #4	0	-0.03 ampere
Pump Case Drain Filter Debris (from bowl and element)	Clean	1. Normal quantity of metallic wear particles. 2. Large number of very small black particles.

Pump performance was satisfactory throughout the test. System pressure was a steady 8000 psi (55 MPa) with nominal pressure fluctuations during rudder actuator operation. The pump had no external leakage or leakage at the shaft seal. A normal quantity of visible metallic wear particles collected in the case drain filter. Total operating time on pump M/N AP1V-106 prior to AFCAS flight testing is summarized below:

	Hours
LHS testing reported in Reference 12	52
LHS testing reported in Reference 13	16
Miscellaneous testing	2
Abex tests (rework to 0.016 CIPR)	5
AFCAS component tests (reported herein)	14
AFCAS simulated flight tests	9
Total	98

Actuator performance was satisfactory throughout the laboratory test. No external leakage occurred except for normal wetting of the piston rod.

Motor running current decreased somewhat during the course of testing (from 156 to 144 amperes). The 1-1/2 hours of continuous operation during a "flight" did not produce overheating; motor surface temperature never exceeded +141°F (61°C).

Operation of the force transducer and EDU was satisfactory. Only slight drifting was observed in the EDU as evidenced by the motor null currents. Response characteristics of the system were unchanged by the test.

A large number of black particles less than 1 micron in size (0.00004 in.) were flushed from the filter element when a patch test was made of debris in the pump case drain filter. This type of particle was observed in a prior LHS test, Reference 11. The source and composition of the particles were not determined; Reference 14 may provide some insight into this. Mobil Oil Corporation has recently developed fluid analysis techniques which disclosed that nitrogen-fixing and thermal cracking cause oil degradation in 3000 psi systems; this may also be occurring at 8000 psi. Effects of the black particles on the operation of 8000 psi systems were considered minimal in view of the excellent performance characteristics observed thus far in both the LHS and AFCAS programs. An experiment involving the use of an inert gas (argon) for reservoir pressurization is currently in progress in an LHS test. This should minimize oxidative-type thermal/chemical reactions and provide an indication whether these reactions (if present) are producing the black particles.

4.2 HANGAR TESTS

4.2.1 Electrical Checks

Procedure details for checking the electrical system are given in Appendix A. A summary of steps taken to assure proper operation of the test system in the T-2C is presented in the following paragraphs.

Continuity checks were made on all AFCAS electrical harness newly installed in the aircraft. Chassis ground checks were conducted to verify that specified pins in the EDU A/C disconnect were grounded. 400 Hz 115 volt power was applied to the harness and measurements were taken to determine that voltage appeared on specified pins in the EDU disconnect. Power was applied to the EDU only. (AFCAS electrical harness was not connected to the force transducers or force motor.) The transducer supply voltage ($\pm$15 VDC) was verified on each transducer disconnect. All the foregoing preliminary checks were completed satisfactorily.

The AFCAS harness was connected to the transducers and force motor. With power applied to the EDU, the rudder actuator piston was moved (by manually deflecting the rudder) so that position transducer output was within $\pm$0.100 volts. The bellcrank-to-surface push rod was then adjusted to obtain $0 \pm 1/4°$ rudder position. Transducer and valve driver output voltages were recorded. Sufficient force was then applied (alternately) to the rudder pedals to produce between 1 and 2 volts DC on the force transducer outputs. The corresponding LED illumination on the AFCAS test box was observed (indicating four hard-over signals). No problems were encountered with any of the foregoing steps.

4.2.2 Hydraulic Checks

Procedure details are given in Appendix A. The first task involved filling and bleeding the 8000 psi (55 MPa) system. The rudder actuator pressure and return lines were temporarily connected together and temporary plumbing was used to join the pump suction line with the discharge and case drain lines (bypassing the 8000 psi pump). A bleed valve was installed in the return line in the RH speed brake well. A ground cart was connected to the aircraft and the system was filled with MIL-H-83282 fluid. With 25 psig (.2 MPa) applied to the T-2C reservoir, air was bled from a port on the heat exchanger and from the bleed valve in the return line.

A leak check was made on the 8000 psi portion of the system using a 0.2 gpm (.76 L/m), 10,000 psi (69 MPa) power supply containing an adjustable relief valve. Pressures up to 8,000 psi were applied; no external leakage occurred. Pressure was increased sufficiently to operate the test system relief valve (9000 psi/62 MPa). No leakage or malfunctions were observed.

The T-2C 3000 psi system was then pressurized with a service ground cart and the various subsystems were operated. No problems were encountered.

4.2.3 System Checkout

System checkout procedure is detailed in Appendix A. Twenty-five psig was applied to the T-2C reservoir and a 300 ampere, 28 volt DC rectifier-type power supply was connected to the aircraft. With electrical power on the aircraft, the motor/pump unit was energized. The cockpit gage was observed to read 8000 psig (55 MPa). Operation of the 8000 psi hydraulic system was satisfactory; no malfunctions or leaks occurred.

The rudder pedals were operated. Rudder control was smooth and positive. A small amount of hysteresis was noted due to normal friction in the cables, pulleys, and bellcranks used in the T-2C directional system. Rudder operation details were determined and are summarized below. Pedal force vs. rudder deflection data are presented on Figure 36.

Description	Data
Maximum rudder deflection	11.8° Right 11.8° Left
Pedal force required for 11.8° rudder	93 lb (414 N)
Pedal deflection at 11.8° rudder	0.5 in. (1.3 cm)
Dead band at 0° rudder	
with cable/pulley friction (no pedal corrections)	1°
with cable/pulley friction minimized (pedals alternately tapped lightly)	1/4°
Moment required to cause rudder to trail with no pressure on rudder actuator, breakout	L→T 325 lb-in (37 N-m) R→T 455 lb-in (51 N-m)

All of the above data were satisfactory.

Temperature of the fluid in the pump suction line versus time was checked with the heat exchanger blower running. The temperature stabilized at +179°F (82°C) after 25 minutes of operating at 8000 psi. In a second test conducted with the heat exchanger blower off, the suction line fluid temperature reached +200°F (93°C) in 24 minutes; stabilization was not achieved.

A pressure transducer was installed (temporarily) in the 8000 psi system pressure line to measure surges and oscillations. Readout was on an oscillograph using a galvanometer with 600 Hz response capability. The maximum

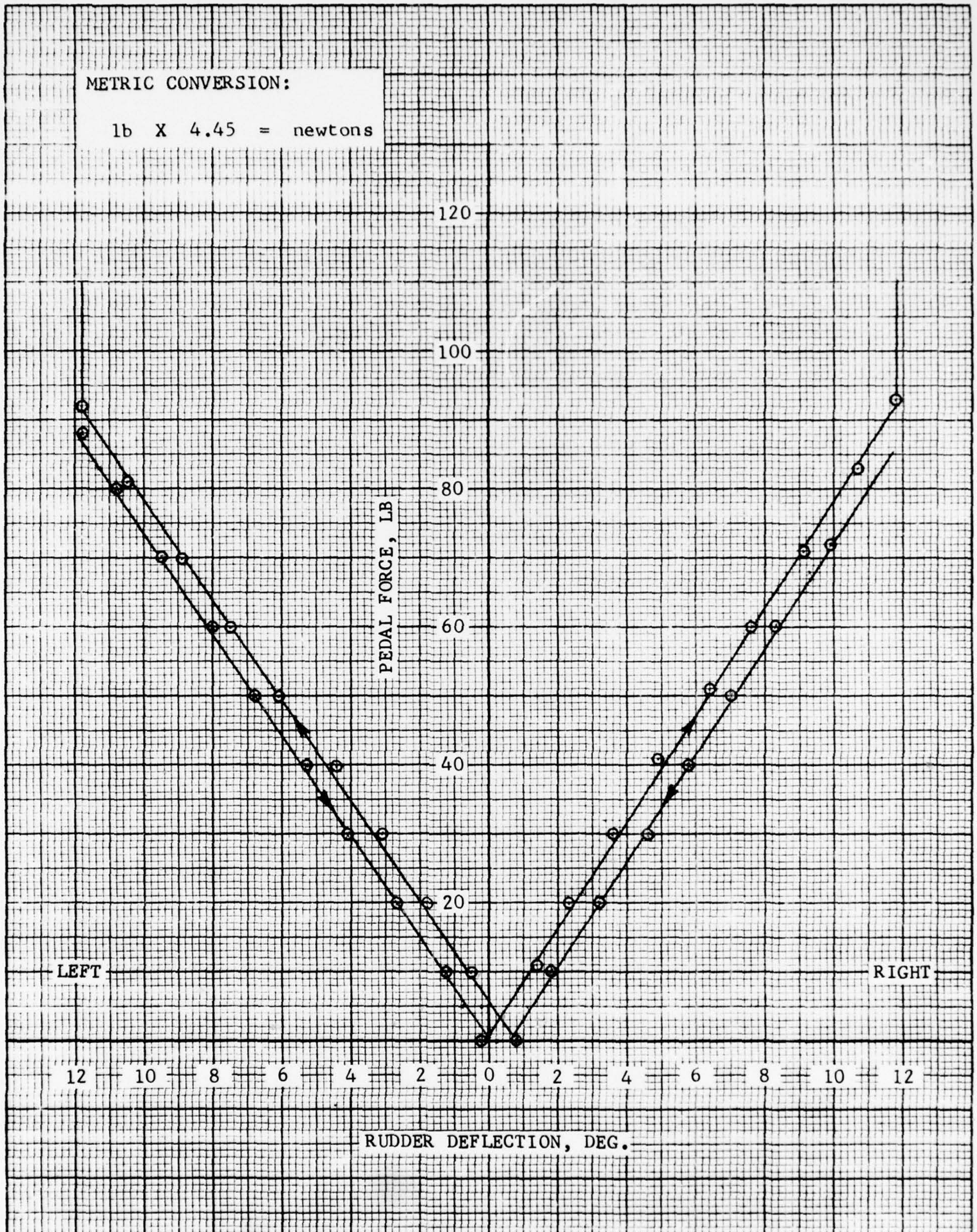


FIGURE 36 PEDAL FORCE VS. RUDDER DEFLECTION

pressure overshoot observed with hard-over inputs to the rudder actuator was 200 psi (1.4 MPa). Pump ripple was less than 100 psi (0.7 MPa) peak-to-peak. No persistent pressure oscillations were present. The 8000 psi system was exceptionally "quiet" with respect to pressure fluctuations.

A visual inspection was made of hydraulic lines in the 8000 psi system to determine if any destructive vibrations were present when the system was operating. No excessive vibratory conditions were observed.

A fluid sample was taken at the conclusion of hangar testing to determine system contamination. Particulate size and quantity were measured with a HIAC automatic particle counter. Contamination was well below NAVAIR 01-1A-17 Class 5 allowables, and was equivalent to a Class 3, Page 95.

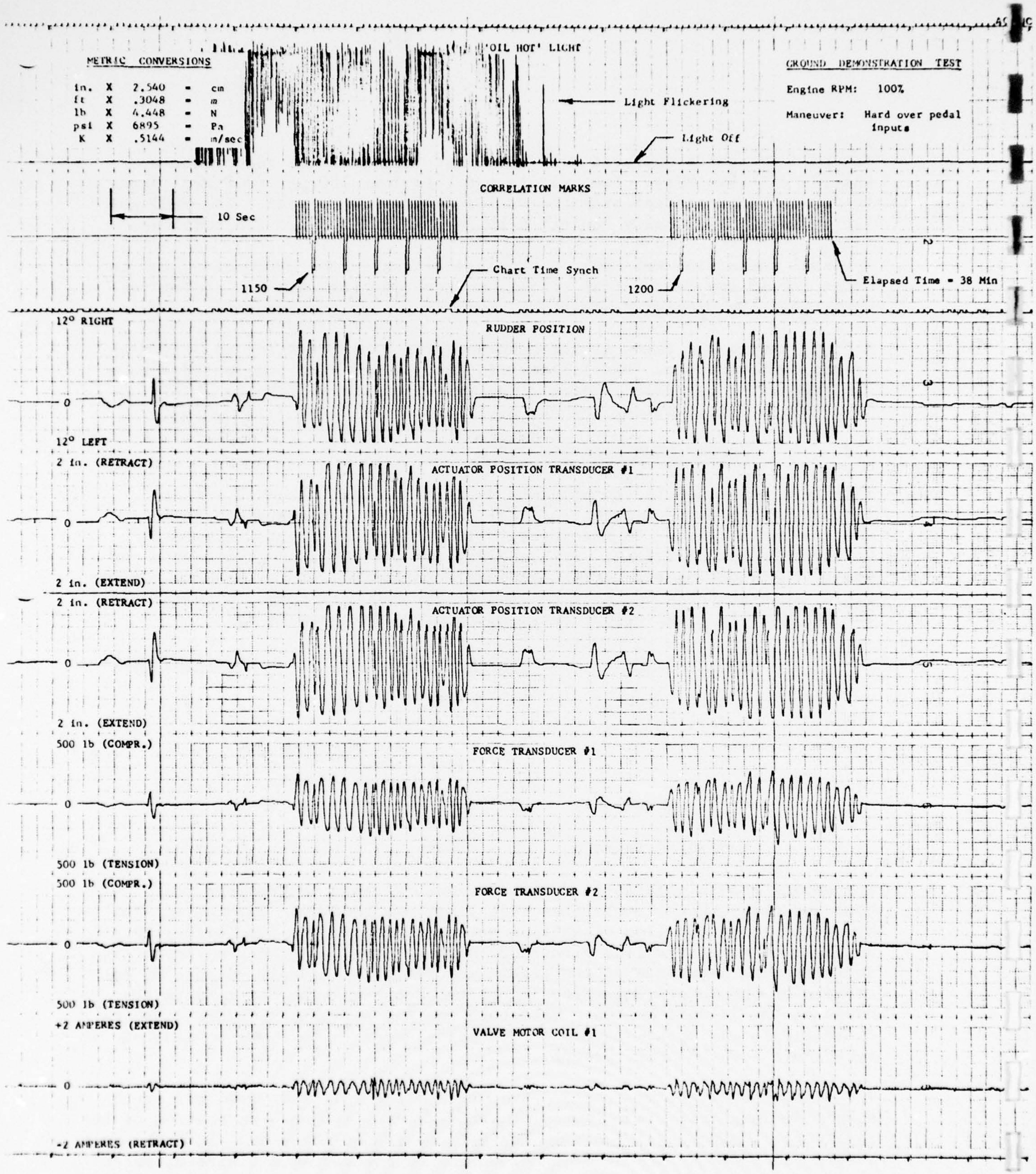
4.3 GROUND DEMONSTRATION TESTS

This test was conducted to simulate a one hour flight from takeoff to landing, and provide a means to final check hydraulic system operation and instrumentation. Engine speed, stick, and pedal inputs were varied to simulate actual flight. Both engines and the motor/pump unit were run continuously during the test. A portable potentiometer was used to monitor fluid temperature in the suction line of the 8000 psi pump. A summary of the "flight" is given below; details are given in Appendix A.

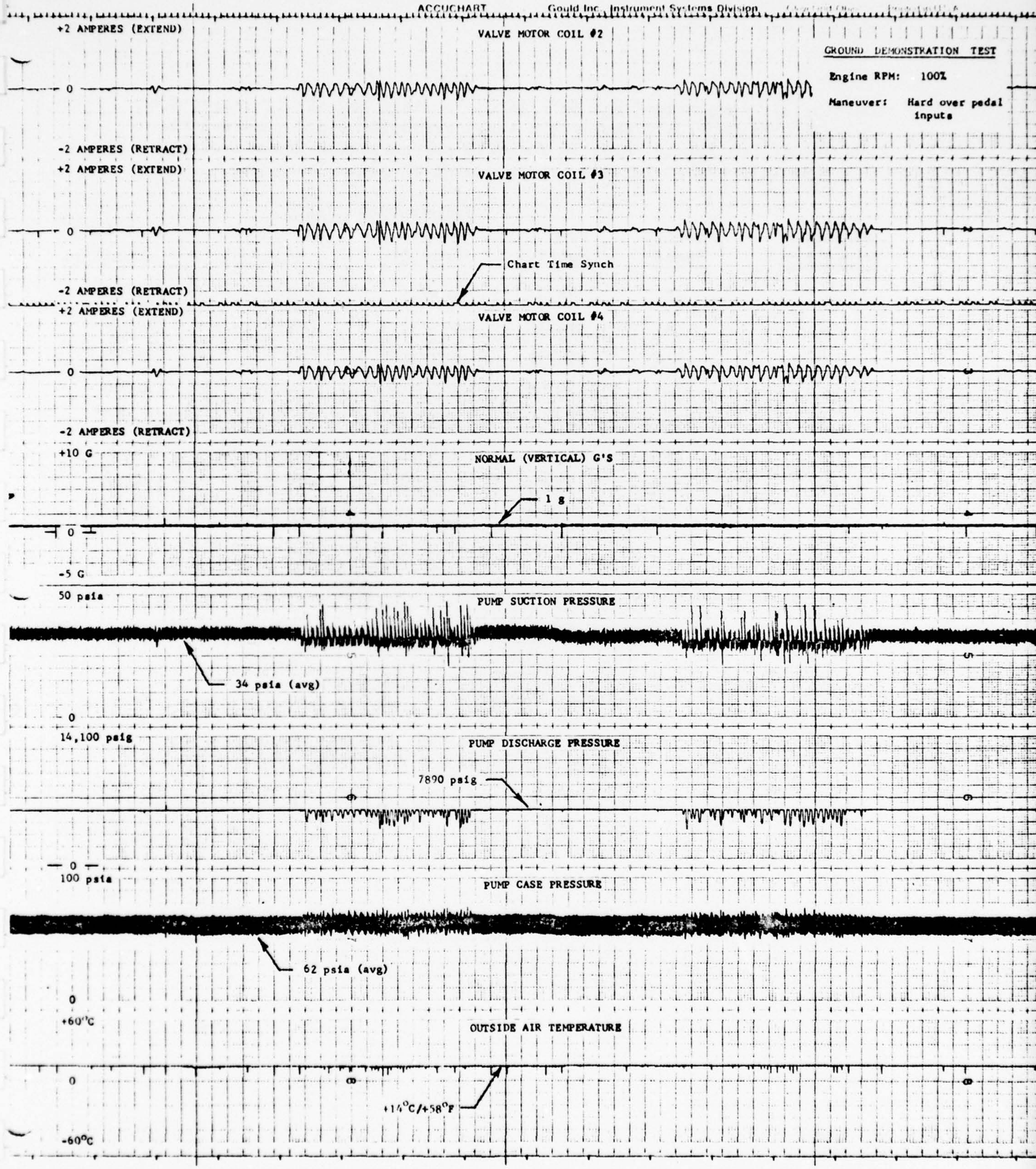
Description	Engine Speed, % MRT	Duration, Min.
System checkout & Taxi Out	48%	10
Takeoff	100%	4
Cruise & Maneuver	80 to 100%	36
Landing & Taxi-In	48%	10

The engine access, hydraulic reservoir, and fuselage compartment doors were open and the vertical stabilizer side panel was removed. Inspections for hydraulic leaks and line vibrations were made during the simulated flight. No leaks or excessive line vibrations were observed. A check was made to determine the magnitude of the ripple imposed on the supply voltage by operation of the motor/pump unit. An oscilloscope was used to measure the noise at the 28 volt DC bus. With both engines operating at idle, the induced ripple was approximately 1 volt peak-to-peak. This was considered acceptable for the AFCAS program.

The simulated flight was stopped prematurely when aircraft fuel was erroneously depleted after 43 minutes of satisfactory testing. Completion of the remaining 17 minutes of run time was not considered necessary since the most severe parts of the test (90% and 100% engine speeds) were finished, reference Appendix A.



METRIC CONVERSIONS
in. X 2.540 = cm
ft X .3048 = m
lb X 4.448 = N
psi X 6895 = Pa
K X .5144 = m/sec
'OIL HOT' LIGHT
Light Flickering
Light Off
GROUND DEMONSTRATION TEST
Engine RPM: 100%
Maneuver: Hard over pedal inputs
CORRELATION MARKS
10 Sec
1150
Chart Time Synch
1200
Elapsed Time = 38 Min
12° RIGHT
RUDDER POSITION
0
12° LEFT
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #1
0
2 in. (EXTEND)
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #2
0
2 in. (EXTEND)
500 lb (COMPR.)
FORCE TRANSDUCER #1
0
500 lb (TENSION)
500 lb (COMPR.)
FORCE TRANSDUCER #2
0
500 lb (TENSION)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #1
0
-2 AMPERES (RETRACT)


ACCUCHART Gould Inc. Instrument Systems Division
GROUND DEMONSTRATION TEST
Engine RPM: 100%
Maneuver: Hard over pedal inputs
VALVE MOTOR COIL #2
+2 AMPERES (EXTEND)
0
-2 AMPERES (RETRACT)
VALVE MOTOR COIL #3
+2 AMPERES (EXTEND)
0
-2 AMPERES (RETRACT)
Chart Time Synch
VALVE MOTOR COIL #4
+2 AMPERES (EXTEND)
0
-2 AMPERES (RETRACT)
NORMAL (VERTICAL) G'S
+10 G
1 g
0
-5 G
PUMP SUCTION PRESSURE
50 psia
34 psia (avg)
0
PUMP DISCHARGE PRESSURE
14,100 psig
7890 psig
0
PUMP CASE PRESSURE
100 psia
62 psia (avg)
0
OUTSIDE AIR TEMPERATURE
+60°C
0
+14°C/+58°F
-60°C

Outside air temperature was 58°F/14°C; fuselage bay air increased from 70°F/21°C to 94°F/34°C during the run. Hydraulic fluid temperatures are summarized below. Flow in the 8000 psi pump case drain averaged 0.85 gpm (3.2 L/m). TM data are presented on pages 80 and 81.

		Temperature, °F/°C			
Elpased Time, Min	Engine Speed	Pump Suction	Pump Case Dr.	Heat Exch. Inlet	Heat Exch. Outlet
1	48%	95/35	165/74	160/71	139/59
9	48%	120/49	195/91	190/88	166/74
14	100%	143/62	213/101	209/98	181/83
25	90%	168/76	227/108	224/107	191/88
28	100%	167/75	233/112	230/110	194/90
34	90%	170/77	233/112	230/110	194/90
37	100%	173/78	234/112	230/110	194/90
40	90%	174/79	235/113	232/111	194/90

Total operating time on the aircraft test installation prior to flight testing was:

	Hours
Hangar Tests	4.0
Ground Demonstration Tests	0.7
Total	4.7

5.0 FLIGHT TESTS

5.1 FLIGHT PLAN

The primary objective was to verify the feasibility of the Advanced Flight Control Actuation System (AFCAS) concept by flight testing a control-by-wire, direct-drive actuation system powered by a localized 8000 psi (55 MPa) motor/pump unit. Demonstration of flying qualities was not part of the program, however pilot comments were encouraged. Ten flight hours were expected to be sufficient to evaluate AFCAS performance, confirm prior analyses and laboratory testing, and provide a measure of confidence in system reliability.

The flight plan was designed to determine directional control characteristics at several altitudes up to 30,000 ft. (9.1 km) and various speeds up to 340 knots (174 m/s). The first two flights were dedicated to confirming satisfactory operation. Subsequent flights were scheduled to evaluate system performance and reliability while accumulating 10 flight hours. Flight plan details are given in Appendix A.

5.2 RESULTS

The AFCAS flights are summarized on Table V. Two pilots participated in the program and prepared reports detailing each test flight. Additional comments were made during flight de-briefings. Both pilots stated that performance of the AFCAS test installation was completely satisfactory. Comments made by the pilots concerning their flights were:

- The AFCAS installation worked exactly as designed
- No malfunctions occurred
- System pressure was steady
- Hydraulic fluid temperatures were normal
- Directional control response was judged to be superior to the production T-2C
- Pilot adaptation to "force control" of the rudder was quickly and easily acquired. Reaction of the aircraft provided the clues to close the loop.
- The force system had an advantage during take-offs and landings in high cross-winds. The fixed pedals provide full rudder and allow much easier braking (in combination) without severe leg and foot extension that is required for conventional deflection controls.

TABLE V

AFCAS OPERATING TIME

AFCAS FLIGHT	DESCRIPTION	PILOT	TIME, HRS GROUND	FLIGHT	REMARKS
	Ground Run	--	.7	--	Simulated Flight
1	T-2C Flt #623	Wenzell	.2	1.3	AFCAS Performance Checks
2	T-2C Flt #624	Wenzell	.1	1.2	AFCAS Performance Checks
3	T-2C Flt #625	Wenzell	.1	1.3	System Endurance Evaluation
4	T-2C Flt #626	Wenzell	.1	1.3	System Endurance Evaluation
5	T-2C Flt #627	Wenzell	.1	1.5	System Endurance Evaluation
6	T-2C Flt #628	Cockburn	.1	1.9	System Endurance Evaluation
7	T-2C Flt #629	Wenzell	.1	1.7	System Endurance Evaluation
		TOTAL	1.5	10.2	

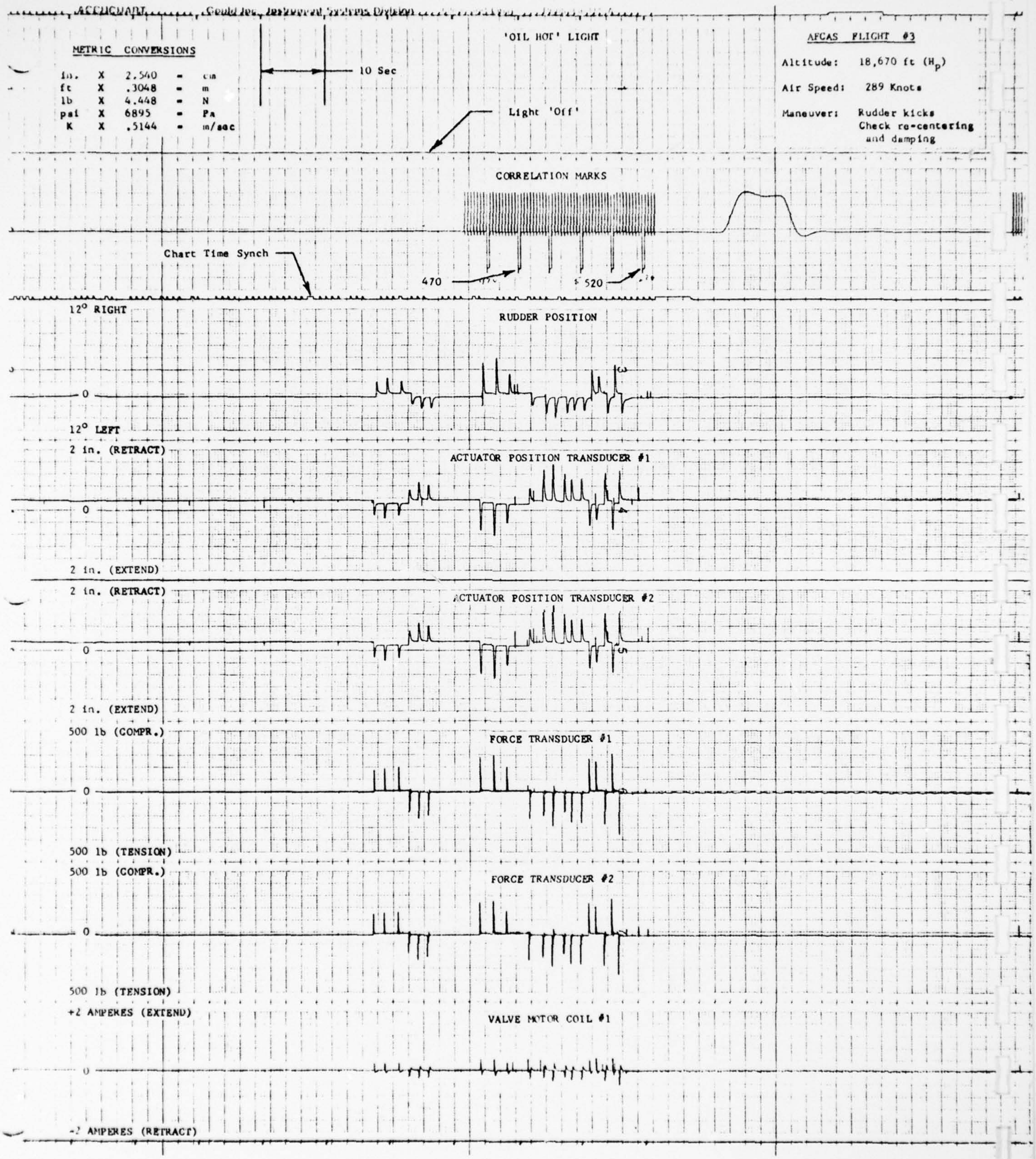
TM data covering various tests and maneuvers are presented on pages 86 through 93. Rudder kicks, shown on page 86, demonstrated that damping was dead beat, and rudder re-centering was rapid and accurate. The ability of air loading on the rudder to drive the actuator to the null position with AFCAS "off" is shown on page 88. Decreasing air loads and actuator rod seal friction prevented the rudder from reaching 0°; the 3° (avg) achieved was considered satisfactory. Sideslip and landing data are given on pages 90 and 92.

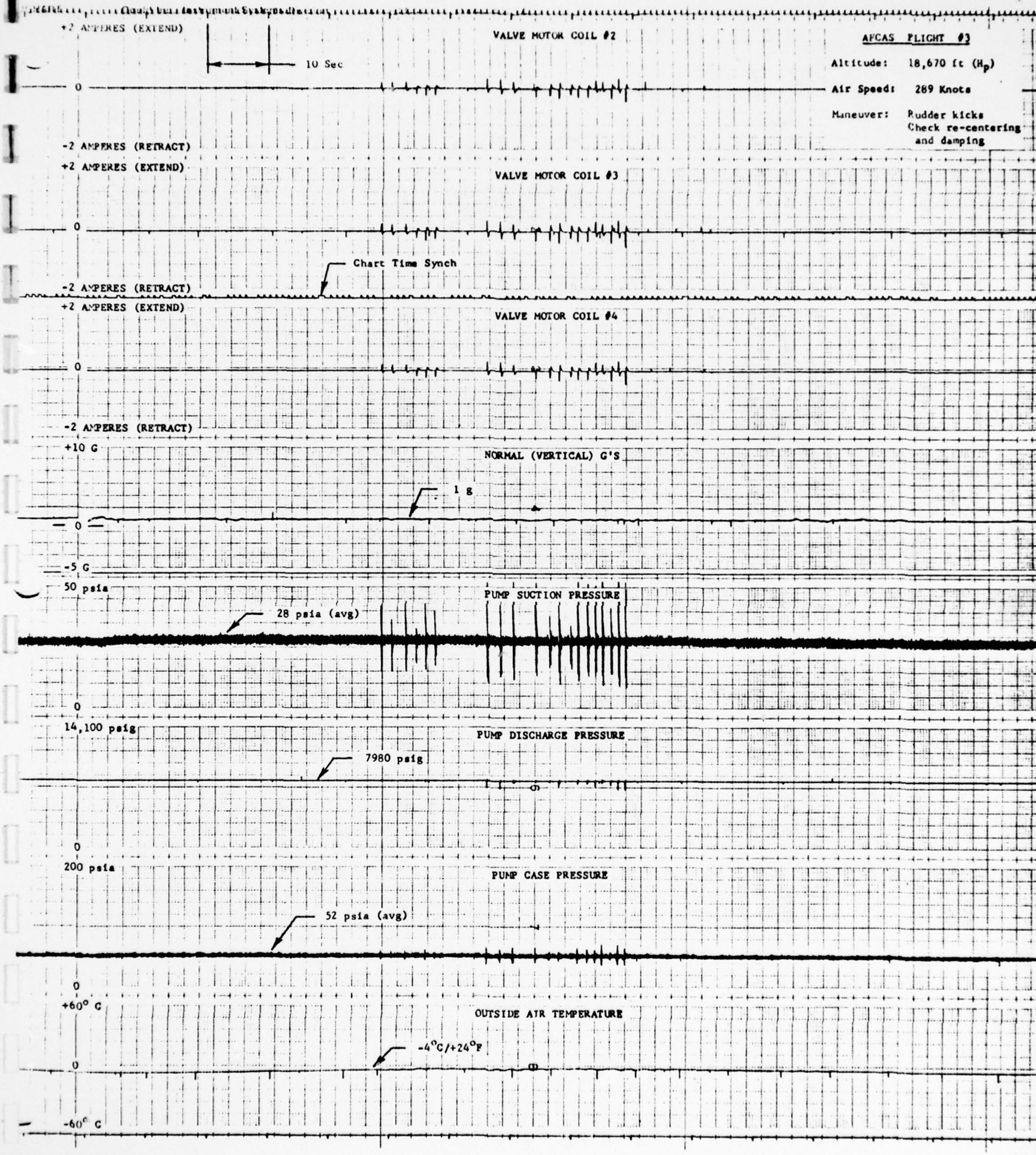
Photo recorder data taken during Flight #4 is presented on page 94. Fluid temperatures were similar for all flights. Pump inlet fluid temperature ranged from +125 to 135°F (52 to 57°C); case drain temperatures were +190 to +200°F (88 to 93°C). Fluid temperature decrease through the heat exchanger averaged 21°F/12°C. A one hour cold soak at 25,000 to 30,000 feet (7.6 to 9.1 km) during Flight #5 produced a compartment air temperature of +13°F/-11°C minimum; outside air temperature averaged -5°F/-21°C. The cold soak did not affect AFCAS operating characteristics. All temperatures were considered to be nominal during the seven AFCAS flights.

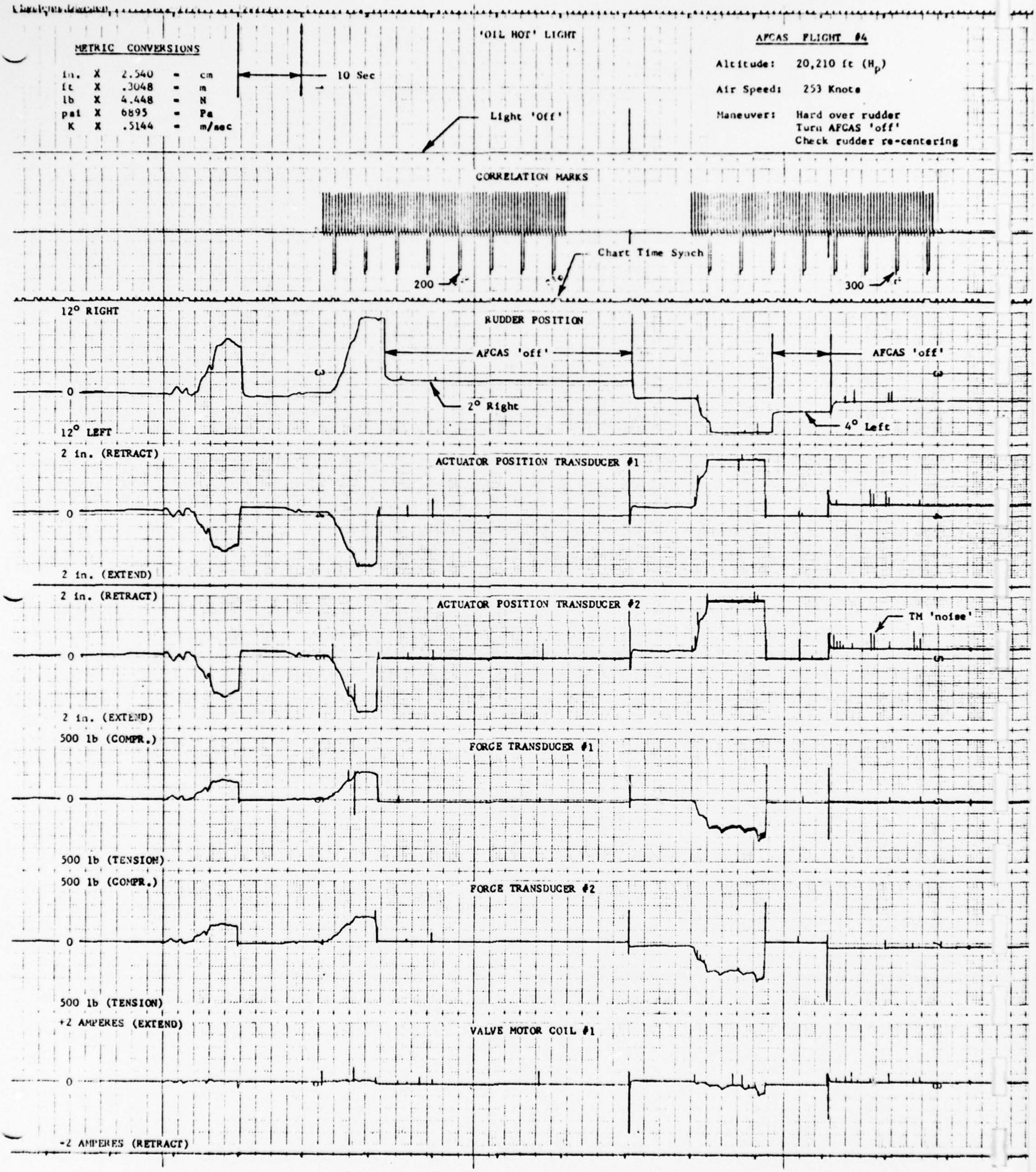
Case drain flow from the 8000 psi pump ranged from .80 to .85 gpm (3.0 to 3.2 L/m) throughout all tests (hangar, ground demonstration, and flight). Flow measured during the "simulated flights" in the laboratory averaged 0.56 gpm (2.1 L/m). Schedule limitations prevented resolution of the difference. Flow instrumentation used in the laboratory was a Fisher and Porter turbine meter with readout on an electronic counter. Instrumentation used on the aircraft was a Flow Technology paddle-wheel meter with readout on a Flow Technology indicator. Since pump case drain flow was unchanged by ground and flight testing, the disagreement was due to an instrumentation malfunction or a calibration discrepancy. The laboratory flow data were considered to be correct.

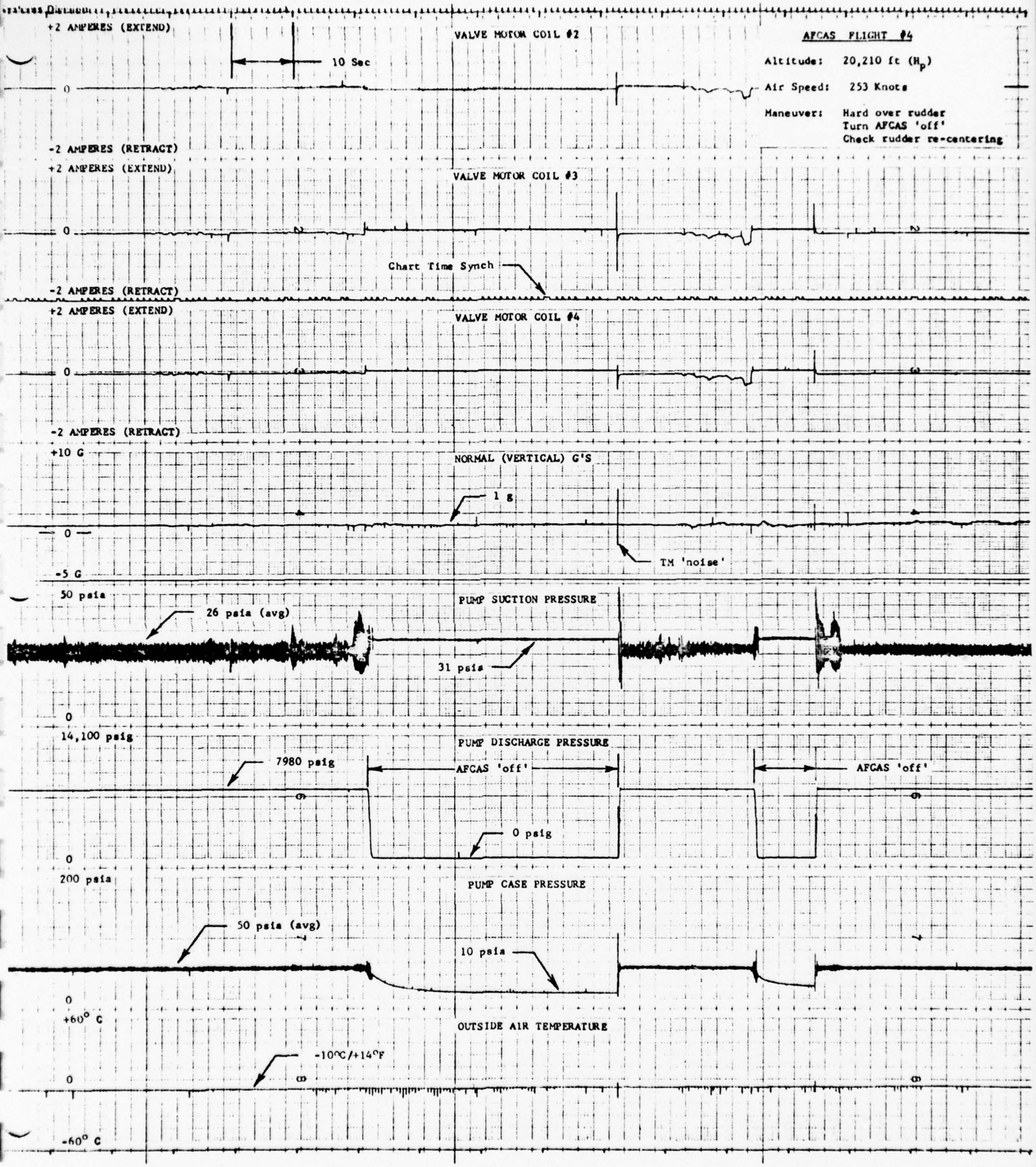
System fluid contamination was measured periodically during the flight program, and after 10.2 flight hours was equivalent to a NAVAIR Class 3, page 95. This low level of contamination was evidence of minimal pump wear and excellent fluid lubricity.

No external leakage occurred in the 8000 psi system based on the fact that the reservoir fluid level remained constant throughout flight testing (the level was noted before and after each flight).

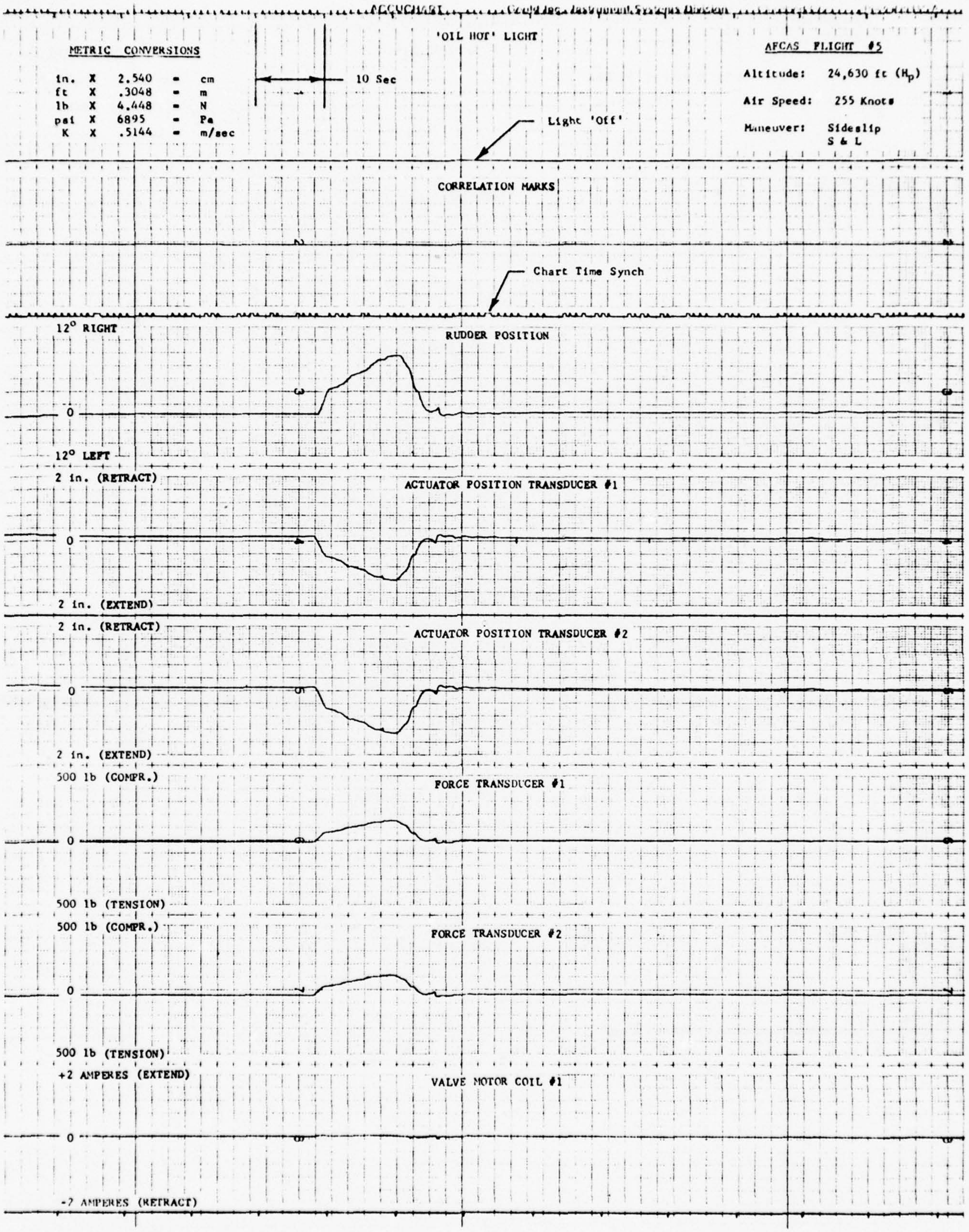

METRIC CONVERSIONS
in. X 2.540 = cm
ft X .3048 = m
lb X 4.448 = N
psi X 6895 = Pa
K X .5144 = m/sec
10 Sec
'OIL HOT' LIGHT
Light 'Off'
AFCAS FLIGHT #3
Altitude: 18,670 ft (Hp)
Air Speed: 289 Knots
Maneuver: Rudder kicks
Check re-centering
and damping
CORRELATION MARKS
Chart Time Synch
470
520
12° RIGHT
RUDDER POSITION
0
12° LEFT
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #1
0
2 in. (EXTEND)
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #2
0
2 in. (EXTEND)
500 lb (COMPR.)
FORCE TRANSDUCER #1
0
500 lb (TENSION)
500 lb (COMPR.)
FORCE TRANSDUCER #2
0
500 lb (TENSION)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #1
0
-2 AMPERES (RETRACT)


AFCAS FLIGHT #3
Altitude: 18,670 ft (H_p)
Air Speed: 289 Knots
Maneuver: Rudder kicks
Check re-centering and damping
10 Sec
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #2
0
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #3
0
Chart Time Synch
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #4
0
-2 AMPERES (RETRACT)
+10 G
NORMAL (VERTICAL) G'S
1 g
0
-5 G
50 psia
PUMP SUCTION PRESSURE
28 psia (avg)
0
14,100 psig
PUMP DISCHARGE PRESSURE
7980 psig
0
200 psia
PUMP CASE PRESSURE
52 psia (avg)
0
+60° C
OUTSIDE AIR TEMPERATURE
-4°C/+24°F
0
-60° C

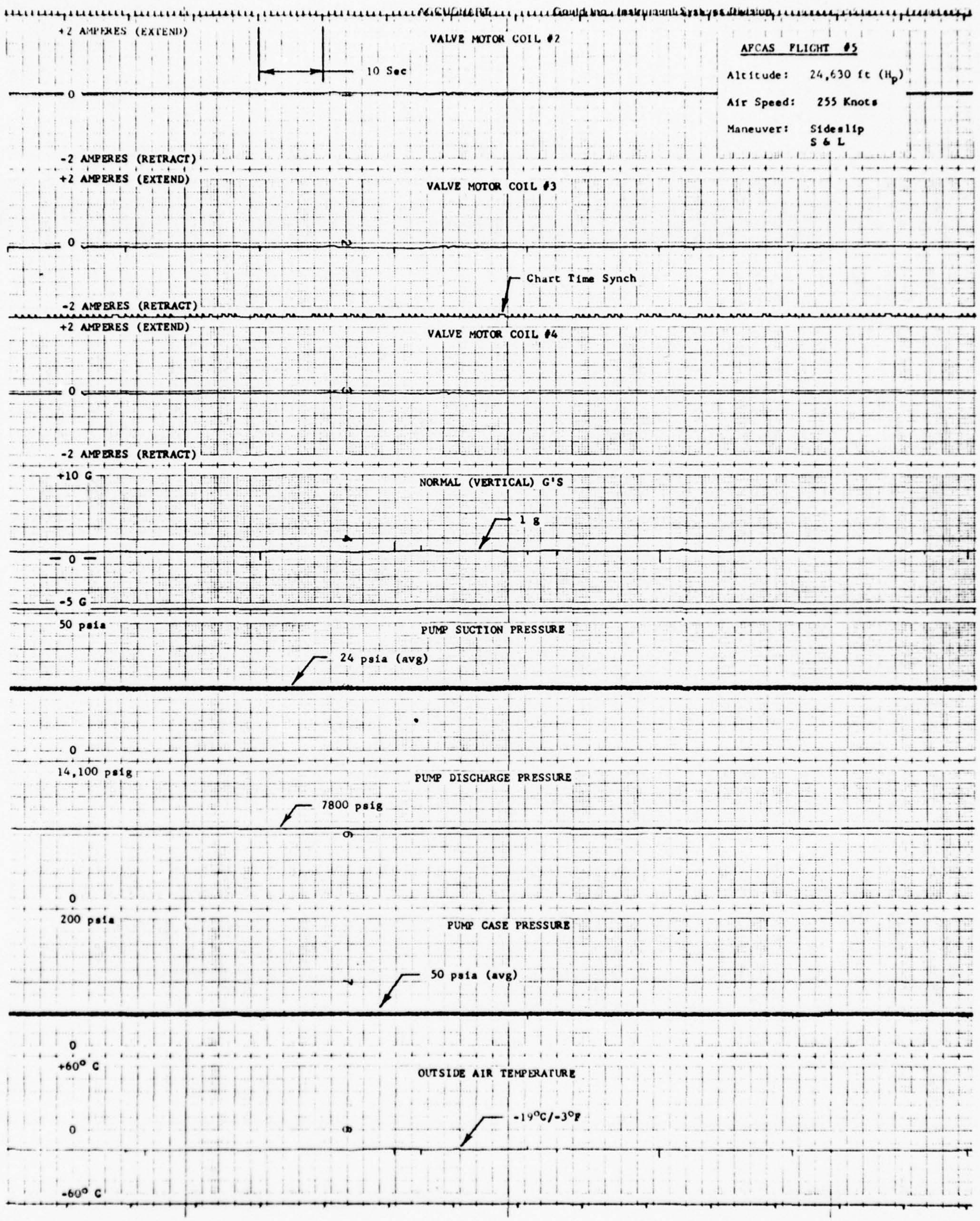

METRIC CONVERSIONS
in. X 2.540 = cm
ft X .3048 = m
lb X 4.448 = N
psi X 6895 = Pa
K X .5144 = m/sec
10 Sec
'OIL HOT' LIGHT
Light 'Off'
AFCAS FLIGHT #4
Altitude: 20,210 ft (H_p)
Air Speed: 253 Knots
Maneuver: Hard over rudder
Turn AFCAS 'off'
Check rudder re-centering
CORRELATION MARKS
Chart Time Synch
200
300
12° RIGHT
RUDDER POSITION
AFCAS 'off'
AFCAS 'off'
0
2° Right
4° Left
12° LEFT
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #1
0
2 in. (EXTEND)
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #2
TM 'noise'
0
2 in. (EXTEND)
500 lb (COMPR.)
FORCE TRANSDUCER #1
0
500 lb (TENSION)
500 lb (COMPR.)
FORCE TRANSDUCER #2
0
500 lb (TENSION)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #1
0
-2 AMPERES (RETRACT)



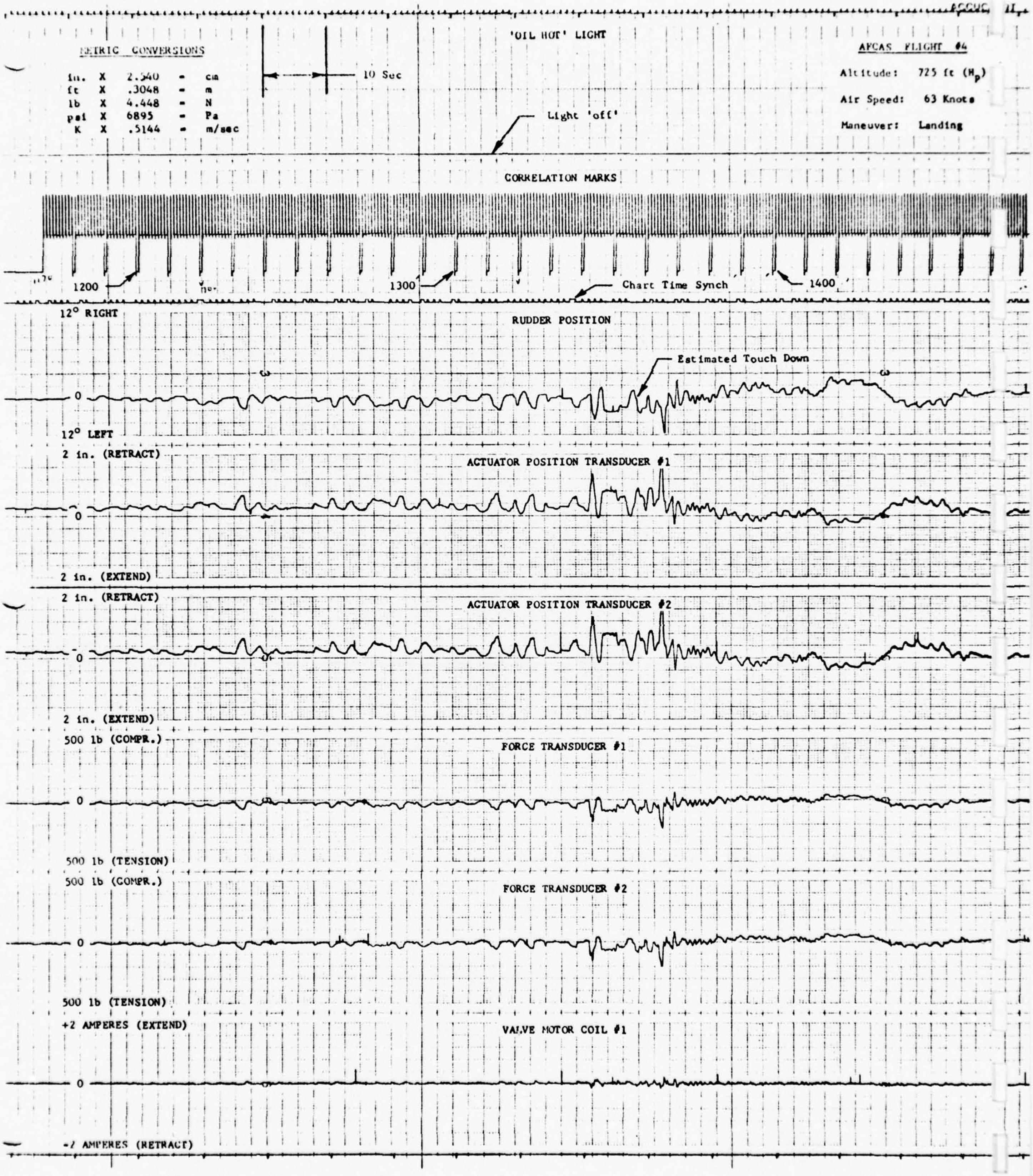
+2 AMPERES (EXTEND)
10 Sec
VALVE MOTOR COIL #2
AFCAS FLIGHT #4
Altitude: 20,210 ft (H_p)
Air Speed: 253 Knots
Maneuver: Hard over rudder
Turn AFCAS 'off'
Check rudder re-centering
0
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #3
0
Chart Time Synch
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #4
0
-2 AMPERES (RETRACT)
+10 G
NORMAL (VERTICAL) G'S
1 g
0
TM 'noise'
-5 G
50 psia
PUMP SUCTION PRESSURE
26 psia (avg)
31 psia
0
14,100 psig
PUMP DISCHARGE PRESSURE
7980 psig
AFCAS 'off'
AFCAS 'off'
0 psig
0
200 psia
PUMP CASE PRESSURE
50 psia (avg)
10 psia
0
+60° C
OUTSIDE AIR TEMPERATURE
-10°C/+14°F
0
-60° C



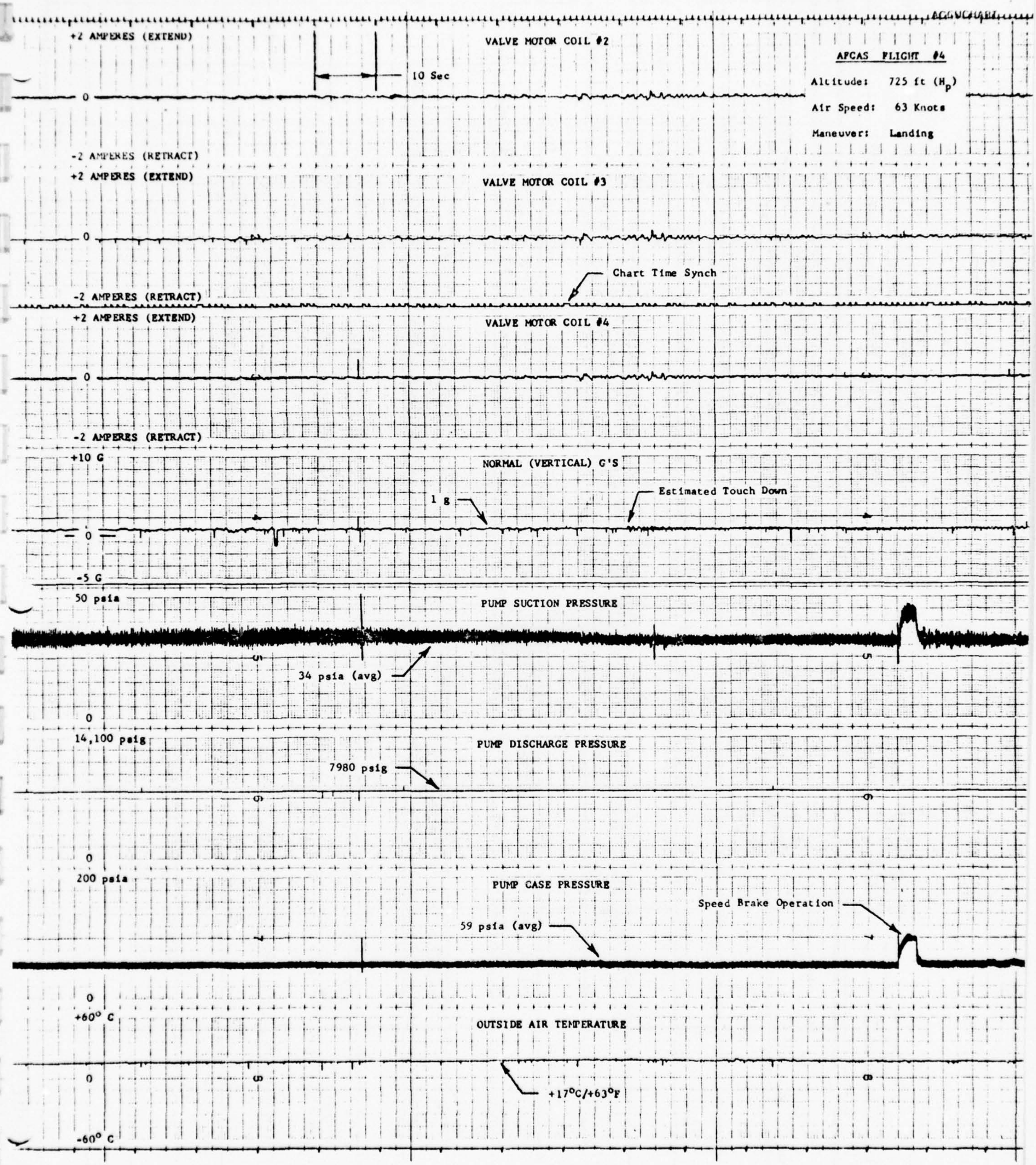
'OIL HOT' LIGHT
METRIC CONVERSIONS
in. X 2.540 = cm
ft X .3048 = m
lb X 4.448 = N
psi X 6895 = Pa
K X .5144 = m/sec
10 Sec
AFCAS FLIGHT #5
Altitude: 24,630 ft (Hp)
Air Speed: 255 Knots
Maneuver: Sideslip S & L
Light 'Off'
CORRELATION MARKS
Chart Time Synch
12° RIGHT
RUDDER POSITION
0
12° LEFT
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #1
0
2 in. (EXTEND)
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #2
0
2 in. (EXTEND)
500 lb (COMPR.)
FORCE TRANSDUCER #1
0
500 lb (TENSION)
500 lb (COMPR.)
FORCE TRANSDUCER #2
0
500 lb (TENSION)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #1
0
-2 AMPERES (RETRACT)



AFCAS FLIGHT #5
Altitude: 24,630 ft (H_p)
Air Speed: 255 Knots
Maneuver: Sideslip
S & L
10 Sec
VALVE MOTOR COIL #2
+2 AMPERES (EXTEND)
0
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #3
0
Chart Time Synch
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #4
0
-2 AMPERES (RETRACT)
+10 G
NORMAL (VERTICAL) G'S
1 g
0
-5 G
50 psia
PUMP SUCTION PRESSURE
24 psia (avg)
0
14,100 psig
PUMP DISCHARGE PRESSURE
7800 psig
0
200 psia
PUMP CASE PRESSURE
50 psia (avg)
0
+60° C
OUTSIDE AIR TEMPERATURE
0
-19°C/-3°F
-60° C



METRIC CONVERSIONS
in. X 2.540 = cm
ft X .3048 = m
lb X 4.448 = N
psi X 6895 = Pa
K X .5144 = m/sec
10 Sec
'OIL HOT' LIGHT
Light 'off'
AFCAS FLIGHT #4
Altitude: 725 ft (H_p)
Air Speed: 63 Knots
Maneuver: Landing
CORRELATION MARKS
1200
1300
1400
Chart Time Synch
12° RIGHT
RUDDER POSITION
Estimated Touch Down
0
12° LEFT
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #1
0
2 in. (EXTEND)
2 in. (RETRACT)
ACTUATOR POSITION TRANSDUCER #2
0
2 in. (EXTEND)
500 lb (COMPR.)
FORCE TRANSDUCER #1
0
500 lb (TENSION)
500 lb (COMPR.)
FORCE TRANSDUCER #2
0
500 lb (TENSION)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #1
0
-2 AMPERES (RETRACT)


APCAS FLIGHT #4
Altitude: 725 ft (H_p)
Air Speed: 63 Knots
Maneuver: Landing
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #2
10 Sec
0
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #3
0
Chart Time Synch
-2 AMPERES (RETRACT)
+2 AMPERES (EXTEND)
VALVE MOTOR COIL #4
0
-2 AMPERES (RETRACT)
+10 G
NORMAL (VERTICAL) G'S
1 g
Estimated Touch Down
0
-5 G
50 psia
PUMP SUCTION PRESSURE
34 psia (avg)
0
14,100 psig
PUMP DISCHARGE PRESSURE
7980 psig
0
200 psia
PUMP CASE PRESSURE
Speed Brake Operation
59 psia (avg)
0
+60° C
OUTSIDE AIR TEMPERATURE
0
+17°C/+63°F
-60° C

A/C T-2C #1 FLT. NO. 626 FILM ☐ TEST/MANEUVER AFCAS FLT #4

PILOT WENZELL DATE 4-28-78 TYPE ____ READ BY RKH

NAV. ____ OSC. ☐ WRITTEN BY ____ PAGE ___ OF ___

NO. ____ CALIB. BY ____

RUN	CORR	TIME	CLOCK	ALT.	A/S	SIDE SLIP	LH ENG.	PUMP C.D.	PUMP SUCT.	1 COMP. AIR	2 PUMP SUCT.	3 PUMP C.D.	4 EDU BOX	5 H.EXCH INLET	6 H.EXCH OUTLET	MANEUVER
			T.O. 2:13	FT	KNOTS	DEG.	RPM	GPM	GPM	°F	°F	°F	°F	°F	°F	
			2:22	20,500	247	7L	6890	.85	.98	+43	131	195	56	190	1.7	RAW DATA
	169		9	20,570	245		6868	.84	.98	+44	+136	+200	+58	+196	+174	YAW
																REDUCED DATA
			2:23	20,800	260	6R	6930	.92	1.18	43	125	187	53	180	161	
	253		10	20,870	256		6908	.91	1.17	+44	+131	+193	+55	+186	+167	R/L SIDE SLIPS
			2:42	21,700	272	1L	6820	.81	1.19	30	125	192	40	185	166	
	429		29	21,780	268		6798	.81	1.18	+30	+131	+198	+41	+191	+173	"S" TURNS
			2:50	19,800	274	6.5L	6860	.85	1.18	32	125	192	40	186	165	
	507		37	19,870	270		6838	.84	1.17	+32	+131	+198	+41	+192	+171	360° ROLLS
			2:51	19,300	275	1R	6870	0	0	33	122	184	40	176	155	
	573		38	19,370	271		6848	0	0	+33	+128	+190	+41	+182	+161	AFCAS OFF
			3:15	20,400	226	0	5500	.85	1.12	33	126	192	36	187	163	
	702		62	20,470	225		5495	.84	1.11	+33	+132	+198	+37	+193	+169	TRIM ROLLS
			3:20	10,500	240	0	4850	.79	1.1	39	124	190	40	184	162	
	949		67	10,500	239		4845	.79	1.09	+40	+130	+196	+41	+190	+168	IDLE DESCENT
			3:29	1250	136	0	6590	.82	1.17	68	120	181	56	175	154	
	1249		76	1280	129		6570	.82	1.16	+70	+126	+187	+58	+181	+160	LANDINGS

DATA SHEET
384 N-1(...63)

Columbus Aircraft Division
QUALITY ASSURANCE LABORATORIES

Rockwell International

TEST REPORT

Date Rec'd in Lab 4-17-78

Article Hydraulic Fluid
Source T2C # 152382
Specification Mil-H-83282
Test Required CONTAMINATION

Quantity 5 ea. as noted
Submitted By:
Name R. Haning
Dept. 071 Ext. 2847

TEST DATA

Date		Class ↓	Results: Number of Particles per 100 ml — Range: 5-15	15-25	25-50	50-100	+100	Comments*
			Max. No					
		5	87000	21400	3130	430	41	
4/17/8	Hydro. Supply	3	6448	586	223	89	43	Preliminary Cleanup.
4/19		3	3106	475	353	17	80	After Ground Demo Test
4/24	#623	3	7761	648	236	77	13	After AFCHS Flight #1
5/1/8	#626	3	2752	221	93	45	5	After AFCHS Flight #4
5/2	#629	3	3849	1469	345	54	14	After AFCHS Flight #7

Disposition and/or Comments:

Signed Harry T. Bayer
Approved
Date 5-3-78

Distribution: W. Bethel D090-B7
W. Doan D054-B3
W.F. Santry D071-543-736

Form H-70-U-1E Rev 2-63 -A

6.0 DISCUSSION

A direct-drive control-by-wire muscle actuator, powered by a localized 8000 psi hydraulic system, was used to control the flight of a T-2C. Successful operation of the test installation represented a significant milestone in the development of advanced flight controls. No problems whatsoever were encountered; the system functioned exceptionally well and pilot response was favorable. The test results confirmed analyses and laboratory investigations reported in References 1 through 4. The ease with which flight testing was accomplished verified that AFCAS type systems can be designed, fabricated, and maintained without special techniques or state-of-the-art advances.

The AFCAS concept is intended for application to automatic, computer operated flight control systems. The current AFCAS flights did not demonstrate the full performance capabilities of the test hardware since the T-2C did not have computer operated controls. Company funded investigations at the Columbus Aircraft Division have verified the feasibility of controlling AFCAS actuators directly by a digital computer. The following section is a brief discussion of this work.

DIGITAL CONTROL OF AFCAS

A laboratory setup was assembled which interfaced AFCAS direct-drive actuation circuits with a PDP-11 programmable digital processor. The processor was equipped with an I/O (input/output) module which converted digital data into analog commands, and which could also be used as a signal buffer for the transmission of digital commands directly to the input stages of the actuator control circuits.

The surface actuation control loop could be closed external to the computer or internal at the computer, Figure 37. With the loop closed externally, computer output corresponded to a surface position command. With the loop closed internally, computer output represented the surface position error signal. The error signal could be a dc analog voltage or, by changing the software, a pulse modulated signal representative of other waveforms.

The PDP-11 processor was used for closed loop control of the direct-drive dual tandem actuator built early in the AFCAS program, Reference 2. The processor was programmed to generate the error signal in four formats: (1) dc analog, (2) pulse-width modulation, (3) bang-bang, and (4) time dwell modulation. Frequency response was determined for all four modes, and was approximately equivalent to that obtained with all-analog control, i.e., without the computer in the loop.

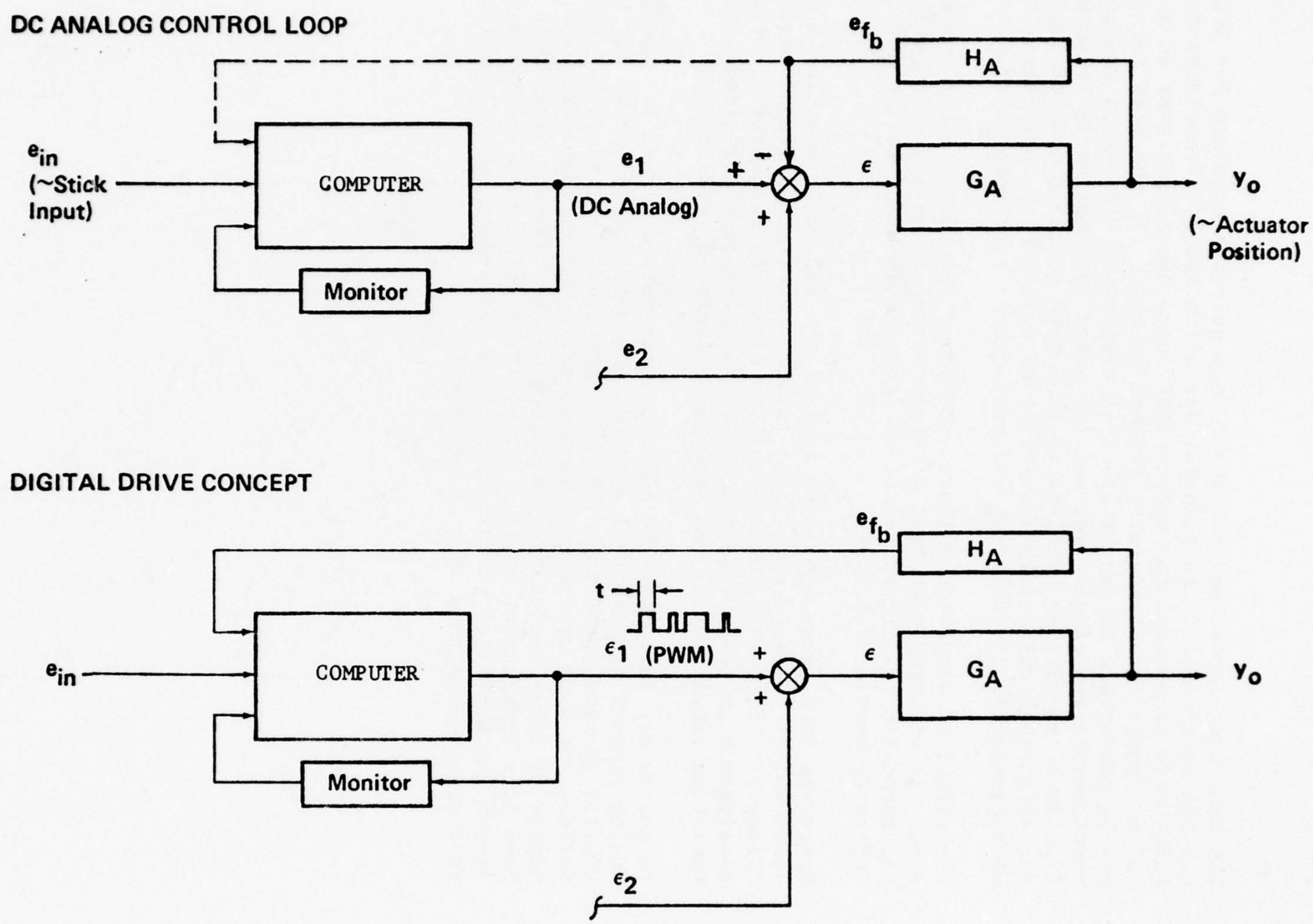


FIGURE 37 COMPUTER CONTROL CONFIGURATIONS

The bang-bang format was ruled out as a suitable waveform for AFCAS control because of rough actuator operation and wear considerations. Pulse modulated waveforms offer significant advantages over dc analog drive signals for fly-by-wire systems because: (1) the need for digital-to-analog converters at each surface is eliminated; (2) fault monitoring requirements are simplified; and (3) power consumption is reduced. Time dwell modulation appeared to be a more suitable mode of control for AFCAS than pulsewidth modulation because TDM is more compatible with passive fault-isolation and produces quieter motor operation.

The effect of simulated failures on closed loop performance was evaluated. It was confirmed that digital control signals are compatible with the automatic failure-compensation features inherent in the EDU concept, reference Section 3.4.3.

Operating in a pulse modulated system, the EDU functions like a high speed switch (Class D amplifier) rather than a proportional amplifier (Class A). Since the control unit is either full on or full off, power dissipation in the EDU is minimal. This increases efficiency, reduces operating temperatures, and results in improved reliability.

Torque motors built for the AFCAS program were designed for use in analog proportional control systems, and were not optimized for use in digital systems operating with pulse modulated (PM) signals. Since failures in a PM system tend to be passive rather than hard-over, the number of coils needed for redundancy may be reduced. The AFCAS motors have four independent coils. Use of three coils in a PM system would lessen the number of circuit components and reduce system complexity. Further study in this area is required.

7.0 RECOMMENDATIONS

Flight verification of the AFCAS concept was completed in Phase V using a system with a direct-drive actuator, localized hydraulic power supply, electronic drive unit, and force transducer. The test installation was an analog control-by-wire system; the AFCAS concept is intended for application to digital control-by-wire systems. The Columbus Aircraft Division has confirmed by laboratory testing that AFCAS components are compatible with digital control-by-wire components. Therefore, it is recommended that the AFCAS test system currently installed on the T-2C be modified by the addition of a micro-processor and that additional flight testing be conducted. This will provide the Navy with an economical approach to demonstrate, in flight, advantages of the direct-drive features of AFCAS with computer control. A further benefit is the availability of a flight test vehicle for future digital control-by-wire developmental effort.

The following tasks are recommended as logical next steps in the AFCAS development cycle:

PHASE VI	<u>FLIGHT DEMONSTRATION OF DIGITAL CONTROL OF AFCAS IN THE T-2C AIRPLANE</u>
Task 1	Procure an off-the-shelf digital micro-processor
Task 2	Program the micro-processor
Task 3	Design the interface electronics and aircraft modifications required to accommodate the additional components
Task 4	Install components and make wiring changes per drawings completed in Task 3
Task 5	Conduct flight testing to demonstrate the computer/ actuator interface method

A second recommendation is concerned with the direct-drive control module (force motor and spool/sleeve valve). The motors and valves procured for prior AFCAS projects were designed for concept verification only, and were not intended to be production configurations. LHS and AFCAS technology have progressed sufficiently that effort can now be directed toward optimized designs which can be integrated into future production applications. The following tasks are therefore recommended: (1) establish force motor design criteria required to achieve a reduced envelope and the reliability necessary for digital control systems; (2) develop classes of control modules to cover the span of actuator classes established in Reference 1; (3) prepare procurement specifications and solicit potential suppliers for the control modules.

REFERENCES

REFERENCE NO.

1 NR72H-240, Feasibility Study for Advanced Flight Control Actuation System (AFCAS), Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-72-C-0108, June 1972, Unclassified. AD 767 058

2 NR73H-107, Control-by-Wire Actuator Model Development for AFCAS, Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-73-C-0405, January 1974, Unclassified. AD 772 588

3 NR75H-1, Control-by-Wire Modular Actuator Tests (AFCAS), Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-73-C-0405, January 1975, Unclassified. AD A-006 371

4 NR76H-1, Design and Fabrication of an 8000 psi Control-by-Wire Actuator for Flight Testing in a T-2C Airplane, Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-75-C-0311, January 1976, Unclassified. AD-A024 487/1GI

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12 J.N. Demarchi and R.K. Haning, Design and Test of an LHS Lateral Control System for a T-2C Airplane, NR76H-14, Columbus Aircraft Division, Rockwell International Corporation, Contract N62269-75-C-0422, May 1976, Unclassified. AD A-032 677

13 J.N. Demarchi and R.K. Haning, Flight Test of an 8000 psi Lightweight Hydraulic System, NR77H-21, Columbus Aircraft Division, Rockwell International Corporation, Contract N62269-76-C-0254, April 1977, Unclassified. AD-A039 717/4GA

14 R.S. Robertson and J.M. Allen, A Study of Oil Performance in Numerically Controlled Hydraulic Systems, Mobil Oil Corporation, Proceedings of the 30th National Conference on Fluid Power, Vol. 28, p. 435, November 1974.

LIST OF ABBREVIATIONS

AC	alternating current
AFCAS	Advanced Flight Control Actuation System
A/S	air speed
alt.	altitude
amp	ampere
approx.	approximately
avg	average
BTU/min	British Thermal Units per minute
°C	degrees Celsius
CAD	Columbus Aircraft Division
cc/min	cubic centimeters per minute
CIPR	cubic inches per revolution
c	centi (10^{-2})
cm^3	cubic centimeters
CORR	correlator
CRES	corrosion resistant
dB	decibel
DC	direct current
deg	degree
EDU	electronic drive unit
°F	degrees Fahrenheit
FRP	flight reference plane
F.S.	fuselage station

ft	feet
ft/sec	feet per second
G	giga (10^9)
gpm	gallons per minute
hp	horsepower
H_p	pressure altitude (29.91 in. Hg = Sea Level)
Hr	hour
Hz	Hertz (cycles per second)
I.D.	inside diameter
in.	inch
in^2	square inches
I/O	input/output
J	joule (metric unit of work)
k	kilo (10^3)
K	knots
kg	kilogram
km	kilometer
KOAS	Knots Observed Airspeed (uncorrected)
kW	kilowatt
L	liter
LED	light emitting diode
L/m	liters per minute
LH, L/H	left hand
LHS	Lightweight Hydraulic System
L/R	left and right

LVDT	linear variable differential transformer
m	meter, also milli (10^{-3}), also minute
M	mega (10^6)
max.	maximum
mm	millimeter
M/N	model number
min	minute (time)
MMH/FH	maintenance man-hours per flight hour
MPa	megapascals
MRT	military rated thrust
MN	mach number, also meganewtons
m/s	meters per second
N	newton (metric unit of force)
NADC	Naval Air Development Center
No.	number
OAT	outside air temperature
O.D.	outside diameter
P-P	peak-to-peak
ΔP	differential pressure
Pa	pascal (metric unit of pressure)
PLF	power for level flight
psi	pounds per square inch
psia	pounds per square inch absolute pressure
psig	pounds per square inch gauge pressure
PM	pulse modulation

P/N	part number
PWM	pulse width modulation
RH, R/H	right hand
rpm	revolutions per minute
s	second (time), also LaPlace transform operator
sec	second (time)
S&L	straight and level
TDM	time dwell modulation
TM	telemetry
T/O	take-off
T	time constant
V	volt
V_h	maximum velocity for level flight
W	watt

SUMMARY OF METRIC CONVERSIONS

Area	in^2	x	6.452	=	cm^2
	ft^2	x	.0929	=	m^2
Fluid Flow	gal/min	x	3785	=	cc/min
	gal/min	x	3.785	=	L/min
	in^3/sec	x	16.39	=	cc/sec
Force	lb	x	4.448	=	N
Heat Flow	BTU/min	x	17.58	=	W
Length	in	x	2.540	=	cm
	ft	x	.3048	=	m
Mass	lb	x	.4536	=	kg
Power	hp	x	.7457	=	kW
	ft-lb/sec	x	1.356	=	W (= J/sec)
Pressure, Stress	psi	x	6895	=	Pa (= N/m^2)
	psi	x	.06895	=	bar
Spring Rate	lb/in	x	175.1	=	N/m
Torque	lb-in	x	.1130	=	N-m
	lb-ft	x	1.356	=	N-m
Velocity, Speed	in/sec	x	2.540	=	cm/sec
	ft/sec	x	.3048	=	m/sec
	knots	x	.5144	=	m/sec
Volume	in^3	x	16.39	=	cm^3 (= cc)
	gal	x	3.785	=	L
	L	x	1000	=	cm^3
	m^3	x	1000	=	L
Work, heat	ft-lb	x	1.356	=	J
	BTU	x	1.055	=	kJ

APPENDIX A

TEST PROCEDURES

This section details procedures used for ground checking and flight testing the AFCAS directional control installation on the T-2 aircraft.

A.1 SYSTEMS CHECKOUT TESTS

1.0 FILL AND BLEED 8000 PSI SYSTEM

A 3000 psi ground cart containing MIL-H-83282 fluid is required.

- Temporarily connect rudder actuator pressure and return lines together. Adaptor fitting provided by Department 071.
- Install bleeder valve furnished by Department 071 in system return line in RH speed brake well. Plug open line.
- Connect plumbing supplied by Department 071 to pump suction line bleed port, pump pressure hose, and case drain line.
- Leave pump case drain port open. Cap pump pressure port.
- Attach ground cart fill line to aircraft. Fill at approximately 1.0 gpm and 85 psi (max.)
- Bleed air from heat exchanger bleed port located at the upper left aft corner of heat exchanger.
- Bleed air at valve in speed brake well.
- Fill reservoir to full mark.
- Dump reservoir pressure.
- Remove temporary plumbing in fuselage compartment and re-install A/C lines. Take care to avoid losing fluid and introducing air.

2.0 LEAK CHECK 8000 PSI SYSTEM

- Connect portable hydraulic power supply (furnished by Department 071) to 8000 psi pressure hose at the motor pump unit. Remove bleed valve and connect power supply return line to the system return line in the RH speed brake well. Lines and fittings furnished by Department 071.
- Apply 1000 psi pressure. Check for leaks. Increase pressure to 4000 psi, then to 8000 psi. Look for leaks.
- Apply pressure sufficient to crack relief valve (8600 to 9000 psi). Do not relieve for more than 15 seconds to avoid overfilling A/C reservoir. Look for leaks.
- Remove portable 8000 psi power supply, re-install bleeder valve in RH speed brake well, and reconnect 8000 psi pump hose hose and case drain line.

3.0 BLEED 3000 PSI SYSTEMS AND OPERATIONAL CHECK

- Connect ground cart pressure pressure and suction lines to aircraft. Make sure pressure line is full of fluid before making connection.

- Connect elevator actuator pressure and return hoses together.

- Apply 100 psi to pressure port. Bleed air at bleeder valve.

- Dump pressure. Reconnect elevator actuator hoses. Remove bleeder valve and reconnect return line in RH speed brake well.

- Apply 3000 psi pressure. Look for leaks.

- Cycle, in order, the following:

	Complete Cycles
1. Speed brakes	10
2. Ailerons	10
3. Arresting hook	5
4. Elevator	10

- Assure proper operation of above subsystems.

4.0 ELECTRICAL WIRING VERIFICATION

- Continuity check all wiring per AFCAS drawing No. 8691-546606.

- Fit check and verify all mating connectors used on rudder actuator, position LVDT's, force transducers, and electronic drive unit (EDU).

- With the EDU, position LVDT's, force transducers, and actuator disconnected, verify that the following aircraft harness pins, and no others, have continuity to aircraft chassis ground:

EDU A/C Disconnect	Pin No.
J4	D
J4	L
J4	P

- Disconnect power plug from heat exchanger blower. Disconnect wire No. C240AOT from terminal A1 of the A4D pump motor relay KA. Protect relay terminals to prevent shorting when electrical power is applied to aircraft busses.

- Connect 28 VDC external ground power cart to aircraft. DO NOT TURN ON.

- Remove relays K108 and K109, #1 and #2 generator bus control relays #3, from relay sockets. Add jumper wire between pins 3 and 5 of both relay sockets, XK 108 and XK 109.

- With the EDU, position LVDT's, force transducers, and actuator disconnected, apply 28 VDC power to aircraft and turn #1 inverter on. Turn hydraulic power switch on.

- Verify there is 115 VAC from J4 on the EDU A/C disconnect, pins N and M, to aircraft ground. Verify that no voltage appears on the remaining pins of this connector and on the LVDT and force transducer A/C disconnects.

- Verify operation of hydraulic pump motor relay KA by testing for 28 VDC present at terminal A1. Turn off #1 inverter and 28 VDC external power.

5.0 SYSTEMS CHECKOUT

5.1 Electrical System

- Connect J4 on the EDU to the A/C harness. Disconnect position LVDT's, force transducers, and actuator motor plugs.

- Turn on 28 VDC ground power supply and #1 inverter.

- Turn rudder hydraulic power switch to "on". Motor/pump unit should not run, but power will be applied to EDU.

- Verify the following voltages:

Disconnect	Pins High	Pins Low	Required Voltage (Tolerance: +0.2 VDC)
Position LVDT #1	E	D	+15 VDC
Position LVDT #1	F	D	-15 VDC
Position LVDT #2	E	D	+15 VDC
Position LVDT #2	F	D	-15 VDC
Force Transducer #1	E	D	+15 VDC
Force Transducer #1	F	D	-15 VDC
Force Transducer #2	E	D	+15 VDC
Force Transducer #2	F	D	-15 VDC

- Turn rudder hydraulic power switch "off". Connect the position LVDT's, force transducers, and actuator motor to aircraft harness.

- Connect J3 on the EDU to the AFCAS test box provided by Department 071.

- Turn rudder hydraulic power switch "on".

- Manually position rudder actuator, using the rudder surface, until the voltages at the actuator LVDT output E for both LVDT's is within $0 \pm .100$ VDC. The rudder surface position shall be $0 \pm 1/4°$. Adjust bell-crank-to-surface push rod as required to obtain $0 \pm 1/4°$ surface position.

- Measure and record the voltages shown on Table I which are available at terminals on the AFCAS test box.

- Apply sufficient pedal force to produce between 1.0 and 2.0 VDC on the force transducer outputs. Observe the corresponding LED illumination on the AFCAS test box during right and left commands.

- Turn rudder hydraulic power switch "off", then turn #1 inverter "off".

- Reconnect wire No. C240AOT to terminal A1 of the hydraulic pump motor relay KA. Insure terminals of relay are protected against shorting. Reconnect plug to power heat exchanger blower. Turn off 28 VDC ground cart.

5.2 Hydraulic System

- Apply 25 psig air pressure to reservoir. Use nitrogen bottle with pressure regulators.

  CAUTION: Operation of the 8000 psi motor/pump unit without engines running requires external reservoir pressurization. Apply air pressure through a capped Tee located near the reservoir pressure regulator.

- Attach temperature potentiometer to thermocouple in motor/pump suction line (furnished by Department 071).

- Disconnect power plug from EDU.

- Insure jumper wires between pins 3 and 5 of relays K 108 and K 109 are in place and secure.

- Apply 28 VDC to aircraft. Turn on #1 inverter. Heat exchanger blower should be running.

TABLE A-I

NOTE: AFCAS POWER ON
HYDRAULIC POWER OFF
RUDDER AT 0^{o} (NULL POSITION)

PEDAL COMMAND	ACTUATOR LVDT OUTPUT E, VDC			FORCE TRANSDUCER OUTPUT E, VDC			VALVE DRIVER OUTPUT E, VDC				
	REQUIRED	#1	#2	REQUIRED	#1	#2	REQUIRED	#1	#2	#3	#4
NO PEDAL	$0 \pm .100$			$0 \pm .125$			$0 \pm .500$				
RIGHT PEDAL	+0.2 MAX.			+1 TO +2			+9 TO +10				
LEFT PEDAL	-0.2 MAX.			-1 TO -2			-9 TO -10				

- Turn rudder hydraulic power switch "on" in cockpit. Observe that pressure is 8000 psi on cockpit gage. Look for leaks.

- Run at 8000 psi until the suction line fluid temperature reaches 210°F or the fluid temperature stabilizes (.5°F rise/minute). Do not run longer than 20 minutes. Record fluid temperature every minute to estimate stabilization temperature and to establish permissible hangar operating time for the 8000 psi system. During the above test, the "oil hot" light should illuminate when the fluid temperature reaches 205 ± 5°F. Reset suction line thermal switch as necessary. If the fluid temperature did not reach 200°F, block the heat exchanger air inlet (right hand side of aircraft) and observe fluid temperature and oil hot light. Do not exceed 210°F fluid temperature. Reset thermal switch as required.

- Turn off rudder hydraulic power switch, #1 inverter and 28 VDC ground power supply.

- Manually push rudder full right and full left to verify trailing capability with hydraulic power off. Measure breakout force required to make rudder trail. Apply load to trailing edge of rudder (not trim tab) opposite push-rod attach point. Protect rudder skin. Record loads.

5.3 <u>AFCAS Installation</u>

- Connect power plug to EDU.

- Turn on 28 VDC ground power supply, #1 inverter, and rudder hydraulic power switch.

- Operate rudder pedals. Assure that rudder operation is satisfactory. Rapidly oscillate rudder a sufficient number of cycles (at least 25) to remove any trapped air within the rudder actuator. Note sensitivity and dead band.

- Apply full right and left pedals. Measure and record maximum rudder deflection. Maximum right and left rudder should be 12 ± 1/2 degree. Determine that rudder returns to 0 ± 3/4 degree with no pedal force.

- Measure and record pedal force and rudder deflection to establish force vs. deflection curve.

- Measure and record rudder pedal travel for maximum rudder deflection.

- Measure and record the voltages shown below with no rudder pedal command.

Description	Required Voltage
Actuator LVDT Output E	0 ± 0.100 VDC
Force Transducer Output E	0 ± 0.125 VDC
Valve Driver Output E	0 ± 0.500 VDC

- Hook up instrumentation provided by Department 071 for measuring pressure transients.

- Operate hydraulic system at 8000 psi and check for detrimental pressure oscillations. Operate rudder and measure pressure surges.

- Hook up oscilloscope provided by Department 071 to 28 VDC terminals on aircraft circuit breaker panel.

- Measure "noise" on 28 VDC bus with motor/pump unit running.

Secure Procedure

- Turn rudder hydraulic power switch "off", then turn #1 inverter "off" and remove external electrical power from aircraft.

- Remove jumper wires from relay sockets XK 108 and XK 109.

- Reinstall relays K 108 and K 109.

- Dump reservoir pressure.

Fluid Contamination Check

- Take fluid sample from reservoir using existing procedures for contamination check. Visually examine case drain and return filter bowls for debris.

A.2 GROUND DEMONSTRATION TESTS

1.0 PREPARATIONS

- Open RH hydraulic bay access door. Open fuselage bay access door. Put steps up to door. Remove vertical stabilizer side panel.

- Attach temperature potentiometer to thermocouple in motor/pump suction line (provided by Department 071).

- Hook up oscilloscope (provided by Department 071) to check "noise" on 28 VDC bus.

2.0 SIMULATED FLIGHT TEST

- The test shown on Table A-II simulates a one hour flight from take-off to landing. Both engines shall be run. Instrumentation will be operated the same as during an actual flight. A "data burst" as used on Table A-II is defined as turning the photo recorder "on" for approximately 15 sec., then "off". The TM oscillograph shall run continuously.

- Monitor pump suction line fluid temperature throughout this test using portable potentiometer. If temperature reaches +200°F, turn hydraulic power switch "off" and shut down.

- Measure "noise" on 28 VDC bus at engine idle with hydraulic power switch "on".

- Take fluid sample from reservoir for contamination check within one hour following ground demonstration test.

- Process film and reduce instrumentation data.

3.0 PREPARATIONS FOR FLIGHT TEST

- Remove pump case drain filter bowl. Deliver bowl, element and fluid to Department 071 for patch test.

- Service reservoir in accordance with Specification HA0201-259, paragraph 4.2.7.

- Mark fluid level position on reservoir sight glass.

- Check instrumentation zeros and R Cals.

TABLE A-II

GROUND DEMONSTRATION TEST

SIMULATION	ENGINE SPEED,%	ELAPSED TIME, MIN.	PHOTO RECORDER	RUDDER, AILERON & ELEVATOR OPERATION
Engine Start	0 to 48%	0 → 1/4	On	No
Hyd. Power Switch "On"			On	
System Check-out & Taxi Out	48%	1	DB	Periodic
		9	DB	
Take-Off	100%	10	DB	Periodic
		14	DB	
	90%	15		
		25	DB	
	100%	26		
		28	DB	
	90%	29		
Cruise		34	DB	Periodic
	100%	35		
		37	DB	
	90%	38		
		43	DB	
	80%	44		
		50	DB	
Landing & Taxi-In	48%	51		Periodic (+ Speed Brakes)
		59	DB	
Hyd. Power Switch "Off"		60	On	
Engine Shutdown	48% to 0	61	On	No

A.3 PILOT INFORMATION

Changes made to the aircraft to incorporate the Advanced Flight Control Actuation System are described herein. The test installation is a fully powered control-by-wire directional system containing:

- Electric motor driven pump
- Rudder actuator
- Electronic drive unit
- Force transducer

The modified hydraulic system will operate at two pressure levels: 3000 psi and 8000 psi. An 8000 psi motor/pump unit has been added to power the rudder system (only). Both engines drive the normal 3000 psi pumps which power the lateral, horizontal, speed brake, and landing gear systems in the usual manner. The 3000 psi and 8000 psi systems share the T-2C reservoir and have common return lines. The test installation is shown schematically on Figure A-1. The modified system will operate functionally the same as the basic T-2C aircraft except rudder operation will not be manual but hydraulically powered. The variable stability system has been deactivated and the speed brakes may be operated using the normal speed brake switch.

The original cable system between the rudder pedals and rudder has been modified to incorporate the control-by-wire system. The rudder pedal cables operate a sector which is prevented from rotating by a force transducer. The rudder pedals will have very little displacement. Force on the pedals is converted to a proportional electrical signal from the force transducer. This command signal is transmitted to the electronic drive unit which conditions the signal and powers a torque motor on the rudder actuator. The torque motor in turn drives a conventional control valve on the actuator. The electrical system contains redundant circuitry which provides high immunity to component failures.

The rudder actuator has a pressure operated bypass valve which permits the rudder to trail if hydraulic power is lost. In the event of a "hard-over" electronic-type failure, the pilot can cause the rudder to trail by turning the 8000 psi rudder hydraulic power system switch to "off".

The rudder trim system is unchanged. Trim response will be different, however, due to the change from a manual to a fully powered rudder. The yaw damper system has been disconnected.

Maximum rudder displacement is reduced from ± 25 degrees to ± 12 degrees. This reduction will permit the pilot to land safely with a "hard-over" rudder, opposite engine out, and a three knot crosswind. The relationship between rudder displacement and pedal force is approximately 8 lb/deg. of rudder movement (93 lb. for full travel).

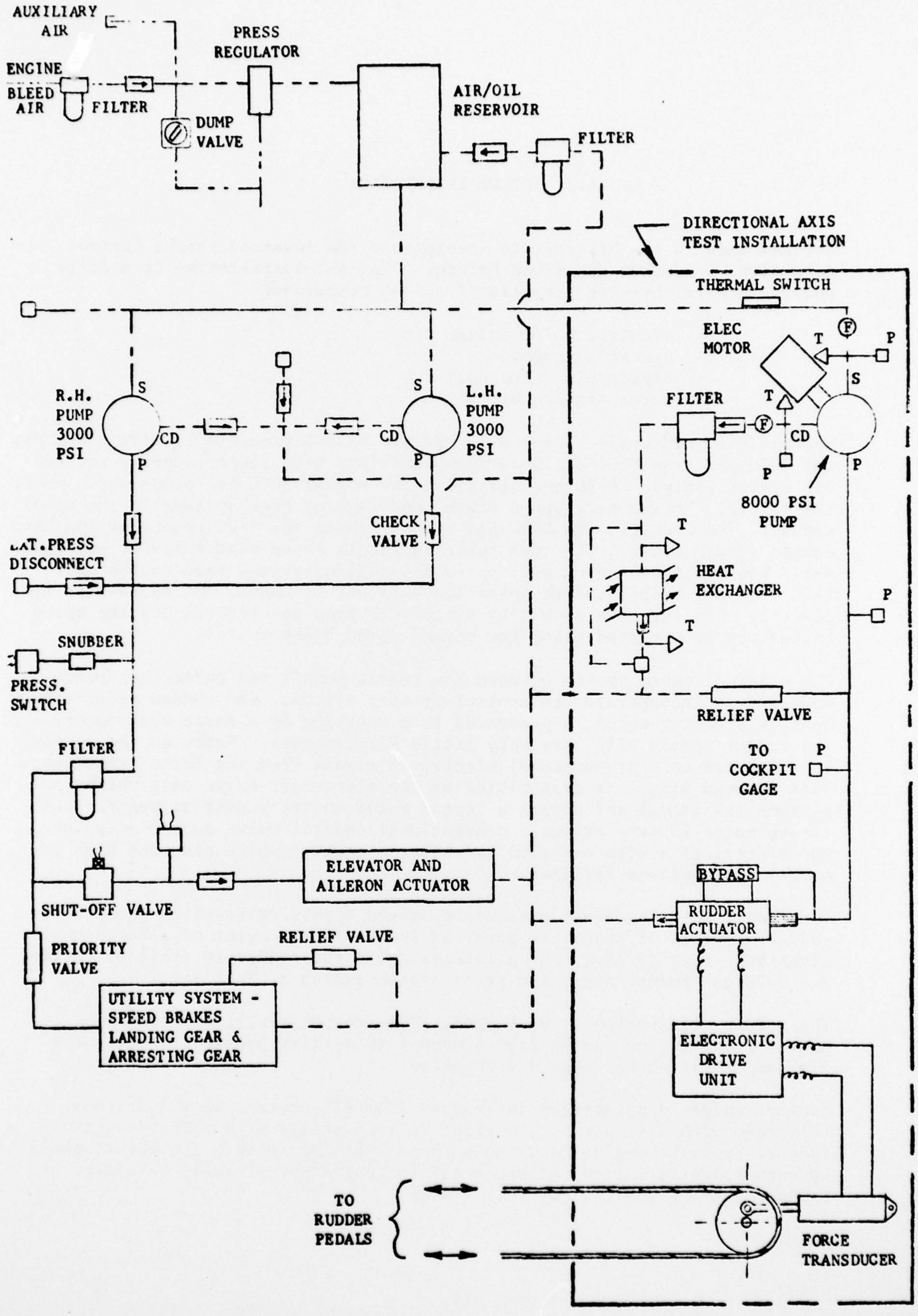

FIGURE A-1 SCHEMATIC DIAGRAM OF MODIFIED HYDRAULIC SYSTEM

Because of the additional load imposed on the 28 VDC generators, the motor/pump unit can be operated only when both engines are running. For this reason, the unit should be turned "on" after both engines have been started and turned "off" before engine shut-down.

Modifications in the cockpit area are as follows:

1. 8000 psi hydraulic pressure on the rudder actuator and electric power to the EDU can be shut off by means of a rudder hydraulic power switch located on the pilot's auxiliary instrumentation control panel (shroud).

   NOTE: For total flight control boost shut-off, the above hydraulic power switch and the normal system boost shut-off switch must be moved to "off". The rudder will trail in this situation and cannot be operated.

2. Output from the 8000 psi pump is displayed on the upper right hand side of the pilot's instrument panel.

   NOTE: The pressure displayed is in the pump discharge line and will fall to zero when the hydraulic power switch is at "off".

3. An oil hot light is provided on the pilot's auxiliary instrument panel (shroud). This light indicates excessive hydraulic system fluid temperature. Actuation of the light is an indication of system malfunction.

Contingency recommendations are:

1. If the left and right yaw responses become significantly different for equal inputs, a malfunction in the system is indicated. Terminate test. Turn the rudder hydraulic power switch "off". Make return flight.

2. If the rudder should become "hard-over", terminate test. Turn rudder hydraulic power switch "off". Make return flight.

3. If the oil hot light comes on, terminate test. Turn rudder hydraulic power switch "off". Reduce power setting and alternately cycle the speed brakes and landing gear during return flight to lower bulk fluid temperature. Stop cycling when fluid temperatures become normal.

4. If the 8000 psi system pressure drops below 6000 psi, terminate test. Turn the rudder hydraulic power switch "off". Make return flight.

5. If it should become necessary to shut-down one engine, turn the rudder hydraulic power switch "off" before engine shut-down.

A.4 FLIGHT TESTS

NOTE: The principal objective is to log 10 hours of flight time on the AFCAS test installation.

FIRST FLIGHT

Maximum Altitude 20,000 Feet
Maximum Speed 250 KOAS

Perform the following maneuvers at 10,000 and 15,000 feet:

- Directional control check with rudder hydraulic power switch "off", $\approx$200 KOAS, PLF (conduct remaining tests with rudder hydraulic power switch "on").
- Level flight MRT 250 K (Max.)
- Idle RPM descent $\approx$ 250 KOAS
- 1/2 directional control, sideslip angle right and left @ 250 KOAS, PLF
- Full directional control, sideslip angle right and left @ 250 KOAS, PLF

SECOND FLIGHT

Maximum Altitude 30,000 feet
Maximum Speed 340 KOAS or .85 MN

*Perform the following maneuvers at 20,000 and 30,000 feet:

- Level flight MRT (no airspeed limit).
- Idle RPM descent $\approx$ 250 KOAS
- 1/2 directional control sideslip angle right and left, @ V_{max} MRT. (This control input may be reduced at the pilot's discretion.)

*Do not operate speed brakes above 20,000 ft.

THIRD AND SUBSEQUENT FLIGHTS

Flight Envelope: Sea level to 30,000 feet
Air Speed: Up to 340 KOAS or 0.85 MN, whichever is less.
Flight Maneuvers: Optional

Flight Data

- Take-offs and Landings:

  Record data continuously during first one minute of take-off and climb and continuously during the one minute prior to touchdown (Flights 1 and 2 only).

- Flight: Record a 15 second data burst once every 10 minutes (all flights).

- Maneuver: Record data continuously during maneuver.

Maneuvers for Pilot Comments

NOTE: Pilot to perform these at his discretion. Recorders not on. Pilot to comment after landing.

- Apply small rudder inputs, note response and dead band.

- Apply pulse inputs, evaluate recentering, left and right.

- Make comparison of CBW "feel" with manual "feel".

- Comment on rudder pedal operation, i.e., no displacement (force only).

- The pilot is encouraged to perform any additional maneuvers that would provide worthwhile data.

Post Flight Checks

- Plot fluid temperature versus time curves from test data. (first two flights and last flight) (performed by Department 071)

- Look for any trends (increase) in pump case flow (Department 071).

- Remove pump case drain filter bowl (first two flights and after final flight). Deliver bowl, element and fluid to Department 071 for patch test.

- Take fluid sample for contamination check (first two flights and after final flight).

- De-brief pilot after each flight.

- Make decisions regarding changes or additional procedures for next flight.

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